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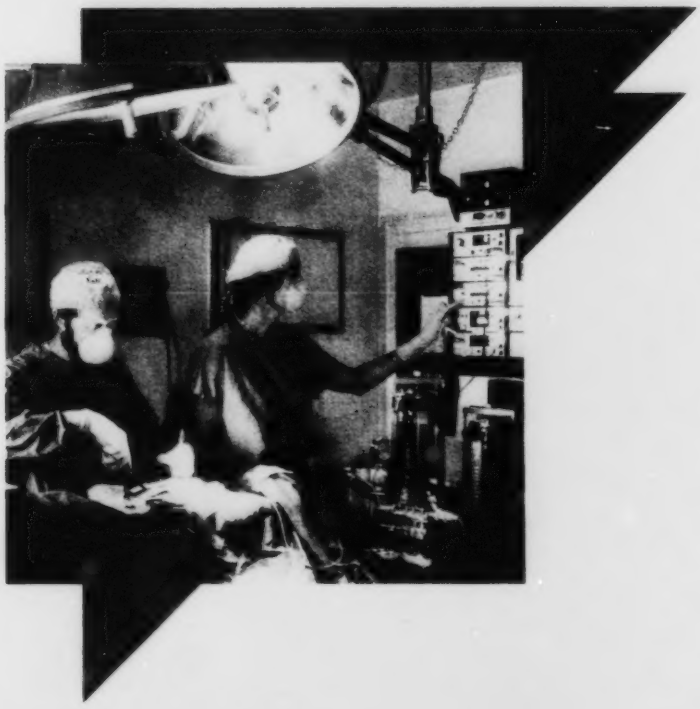
Influence of Handrail Height and Stairway Slope on the Ability of Young and Elderly users to Generate Stabilizing Forces and Moments

B.E. Maki

August 1988



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INFLUENCE OF HANDRAIL HEIGHT AND STAIRWAY SLOPE

ON THE ABILITY OF

YOUNG AND ELDERLY USERS TO GENERATE STABILIZING FORCES AND MOMENTS

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March 30, 1984

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SUMMARY

The purpose of this study was to determine the influence of handrail height on stairway safety, for the purpose of improving building design standards. The present study is an extension of previous work to include stairway slopes of 41 and 49 degrees. The previous experiments were conducted at a slope of 33 degrees.

In preventing a stairway fall, the functional role of the handrail is to generate stabilizing forces and moments. The horizontal and vertical forces counteract undesirable forward and downward motion of the body. The moment generated about the metatarsophalangeal joints of the supporting foot counteracts the de-stabilizing moment due to body weight as well as the rotational momentum of the body.

The experiments involved measurement of the maximum stabilizing forces and moments that subjects were able to generate while standing stationary in an upright position. Changes in body position and orientation would be expected to change the forces and moments generated during an actual fall; however, static measurements of maximum voluntary effort (made in an erect posture) represent a reasonable approximation of the maximum stabilizing forces and moments that could be generated during the initial stage of a fall. It is felt that such measurements provide a suitable basis for the comparison of handrail heights.

The subjects were restrained to control body position and to provide sufficient reaction forces on the body while pushing on the handrail. The handrail support was cantilevered and mounted to a force plate, so that the components of the applied force and moment in the sagittal plane could be measured. Measured forces and moments were normalized with respect to each subject's destabilizing body weight and associated moment, in order to quantify the potential stabilizing effect relative to corresponding destabilizing factors. Normalization allowed different subjects to be compared on a physically meaningful basis. Two age groups were tested: young (20 to 45) and elderly (59 and over), to examine possible age differences. Twenty subjects were tested for each age group.

Statistical analysis of the results showed that changes in handrail height did have a significant effect on the ability to generate stabilizing forces and moments, and that significant age differences did exist in this ability. Moreover, all subjects showed a strong linear dependence on handrail height in generating stabilizing forces and moments. Ability to generate forward/backward forces and forward/backward moments increased linearly with increasing handrail height. Ability to generate upward force decreased linearly with increasing handrail height. Similar results were found at both slopes.

Based on the force/moment data and on subjective user preference, an optimal design range for handrail height was estimated to be 36 to 38 inches (inclusive) for both slopes. The mean subjective preference was found to be approximately 36.5 inches at both slopes.

RÉSUMÉ

Le but de cette étude est de déterminer l'effet de la hauteur de la rampe sur la sécurité dans les escaliers afin d'améliorer les normes de conception des bâtiments. La présente étude fait suite à d'autres travaux et porte sur des escaliers ayant des pentes de 41 et de 49 degrés. Les expériences antérieures ont été faites pour une pente de 33 degrés.

Dans la prévention des chutes dans les escaliers, la fonction de la rampe est de fournir des forces et des moments de stabilisation. Les forces horizontales et verticales doivent contrer les forces indésirables vers l'avant et vers le bas qui s'exercent sur le corps. Le moment produit au niveau des articulations métatarso-phalangiennes du pied d'appui contre le moment déstabilisant dû au poids et à l'élan rotatoire du corps.

Les expériences consistaient à mesurer les forces et moments de stabilisation maximaux que pouvaient produire les sujets debout en position stationnaire. Les variations dans la position et dans l'orientation du corps auraient sans doute un effet sur les forces et moments produits lors d'une chute réelle; toutefois, les mesures statiques de l'effort volontaire maximal (en position debout) permettent d'obtenir une approximation valable des forces et moments de stabilisation maximaux pouvant être générés aux premiers instants d'une chute. On croit que ce type de mesure fournit une base valable pour la comparaison de différentes hauteurs de rampe.

Les sujets devaient contrôler la position du corps et fournir les forces de réaction suffisantes en poussant sur la rampe. Le support de la rampe était monté en porte-à-faux et relié à un capteur de charges de façon que les composantes de la force et du moment appliqués dans le plan sagittal puissent être mesurées. Les forces et moments mesurés ont été pondérés en fonction du poids et du moment déstabilisant de chaque sujet afin de quantifier l'effet stabilisant potentiel contrant les facteurs déstabilisants correspondants. La pondération a permis de comparer des sujets différents sur des fondements physiques significatifs. Les essais ont porté sur deux groupes d'âge : les jeunes adultes (20 à 45 ans) et les personnes âgées (59 ans et plus) afin de connaître les écarts possibles selon l'âge du sujet. Vingt sujets ont subi l'essai dans chaque groupe d'âge.

L'analyse statistique des résultats a démontré que la hauteur de la rampe a un effet important sur la capacité de produire les forces et moments stabilisants et que cette capacité variait beaucoup avec l'âge. De plus, chez tous les sujets, on a noté une forte dépendance linéaire entre la hauteur de la rampe et la capacité d'exercer les forces et moments de stabilisation. La capacité de produire des forces et des moments vers l'avant et vers l'arrière augmentait linéairement avec la hauteur de la rampe. La capacité d'exercer une force vers le haut diminuait linéairement à mesure que la hauteur de la rampe augmentait. Des résultats similaires ont été obtenus pour les deux pentes d'escalier.

À partir des données forces-moments obtenues et des préférences subjectives des sujets, on a estimé que la hauteur de la rampe devrait se situer entre 36 et 38 pouces (inclusivement) pour les deux pentes. La préférence subjective moyenne se situait à environ 36,5 pouces pour les deux pentes.

ACKNOWLEDGEMENTS

I would like to thank and acknowledge the following staff members at West Park Research for their invaluable assistance in completing this project: Linda Maw, for running the experiments; Richard Lobb, for modifying the experimental apparatus; and Sheryl Bartlett, for designing the statistical analysis.

I would also like to thank the experimental subjects for their participation.

Brian Maki
March 30, 1984

NOTE ON UNITS OF MEASUREMENT USED IN THIS REPORT

All measurements are reported using the S.I. system, with the exception of handrail height. For historical reasons, handrail height is reported in inches. The following conversion applies:

1 inch = 25.4 mm

Therefore:

32 inches	=	812.8 mm
34 inches	=	863.6 mm
36 inches	=	914.1 mm
38 inches	=	965.2 mm
40 inches	=	1016.0 mm
42 inches	=	1066.8 mm

I INTRODUCTION

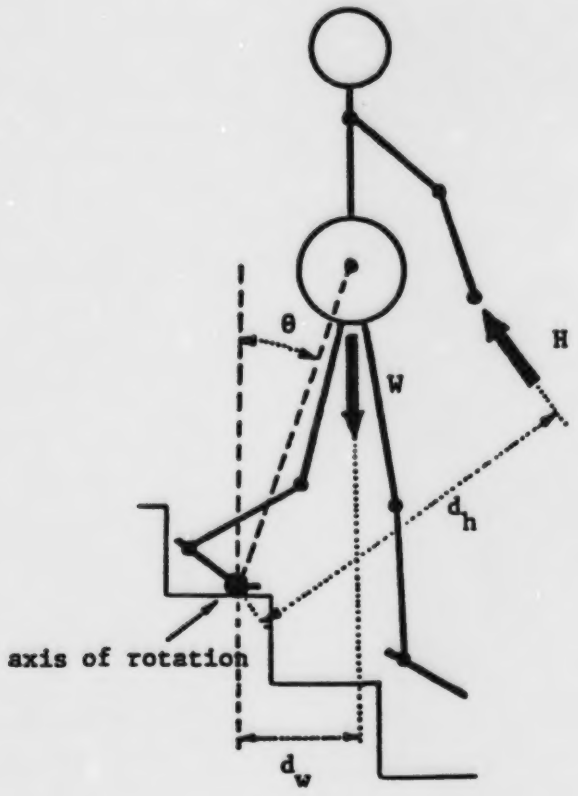
Stairway falls are one of the most common causes of accidental injury (Templer, 1974). These falls are particularly serious in elderly stairway users, because of their susceptability to bone fracture (Brocklehurst, 1978). If properly designed, handrails should reduce the incidence of stairway falls; however, existing design standards have been derived with little regard to basic biomechanical principles (Maki and Fernie, 1983).

The overall objective of our work is to evaluate the effects of changes in handrail design on stairway safety, in order to develop more appropriate design standards. In our previous study (Maki and Fernie, 1983), we investigated the influence of handrail height on stairway safety at a single stairway slope of 33 degrees. The work described in this report is essentially an extension of the initial experiments to include slopes of 41 and 49 degrees. Combined, the two studies are intended to provide a basis for handrail design over a wide range of stairway slopes.

Evaluation of the effectiveness of a given handrail design in preventing falls could involve: (1) in-the-field observation of stairway falls, or (2) laboratory studies using applied postural perturbations. The first approach is not practical, due to the low incidence at which falls normally occur and the lack of control over other variables (characteristics of the subjects, speed of gait, stairway traffic, etc). The second approach raises serious safety concerns. Even if a safety harness is used, the technique represents substantial risks for elderly subjects. Because of the difficulties inherent to the study of actual falls, an indirect method of assessment was developed, based on simple biomechanical principles.

In preventing a stairway fall, the functional role of the handrail is to generate stabilizing reaction forces and moments on the body. These forces and moments act on the body in reaction to the forces exerted by the hand on the handrail (see Figure 1.1). The horizontal and vertical forces counteract undesirable forward-backward and downward motion of the body. The stabilizing moment is also important. Modelling the initial stages of a fall as inverted-pendulum rotation about the metatarsophalangeal joints of the supporting foot, the moment generated by the handrail forces counteracts the rotational momentum of the body and the de-stabilizing moment due to body weight.

The experiments involved measurement of the maximum forces and moments that subjects were able to exert on a handrail, while standing stationary in an upright position. During the tests, the subjects were restrained so as to provide sufficient reaction forces on the body and to maintain the body in an upright position. Increases in the generated moment and force were regarded as being indicative of an enhanced ability to counteract de-stabilizing moments and forces and to thereby recover from a loss of balance without falling.



Legend: θ = angle of inclination of inverted pendulum
W = body weight; d_w = moment arm of body weight
H = handrail force; d_h = moment arm of handrail force

Note: de-stabilizing torque = $W \times d_w$
stabilizing torque due to handrail = $H \times d_h$

Figure 1.1 Biomechanical Model of the Stairway User

II METHODOLOGY

The experimental methodology was identical to that used in the previous study except that the experiments were performed at stairway slopes of 41 and 49 degrees, rather than 33 degrees. The same group of subjects was tested at both slopes. Approximately 45% of the subjects in the present experiments participated in the previous experiment.

The two slopes were tested in separate experimental sessions, conducted on separate days or on the same day with a resting period of 30 minutes between sessions. The order in which a given subject was tested at the two slopes was randomized, to prevent possible bias in the results due to learning effects.

A summary of the methodology appears below. For more details, consult the previous report (Maki and Fernie, 1983).

(1) Apparatus

The experimental apparatus, shown in Figure 2.1, included: (1) two mock stairways (slopes of 41 and 49 degrees), (2) subject restraints, (3) a test handrail, and (4) a force measurement system.

The mock stairways had standard tread and riser dimensions. The 41-degree stairway had a tread of 9 inches (229 mm) and a riser of 8 inches (203 mm), while the 49-degree stairway had a tread of 8 inches (203 mm) and a riser of 9 inches (229 mm). Both stairways had an overhang (projected nosing) of 1 inch (25 mm) which is not included in the tread dimensions listed above.

The mock stairways could be moved to allow the lateral displacement of the subject to be adjusted. Subjects were restrained posteriorly by a rigid, foam-cushioned back-board, and anteriorly by a canvas harness. The handrail was mounted on a rigid, cantilevered column, which was bolted to a piezoelectric force plate (Kistler, Model 9281). The height and slope of the handrail were adjustable. The force plate was used to measure forces and bending moments in the sagittal plane. The output of the force plate was fed to charge amplifiers (Kiag Swiss, Model 5001), and was then sampled at rate of 20 Hz, using an analog-to-digital converter unit (Neff, Model 920) and a minicomputer (Hewlett Packard, Model 9845). The sampled data was stored on magnetic disc, for later analysis. The computer software plotted out the time records of the measured force and moment following each experimental trial, so that the trial could be repeated if necessary.

The experimental apparatus was calibrated by hanging weights at known moment arms. Horizontal and upward vertical forces were achieved by means of a pulley arrangement. Mean error was less than 10% and correlation between applied and measured loads was 0.997 or better.

Figure 2.1 The Experimental Apparatus

Legend:
1. mock stairway
2. restraining back-board
3. tracks (for adjusting lateral displacement)
4. scale for measuring lateral displacement
5. handrail
6. support for handrail
7. scale for measuring height of handrail
8. force plate

(2) Subjects

The study used only normal subjects, that is subjects with: (1) no evidence of significant neurological, vestibular, arthritic or musculoskeletal disorders or deficits, (2) no history of abnormal problems with dizziness or falling, and (3) no present regimen of drugs or medications that might affect neuromuscular function. Two age groups were studied: twenty subjects (8 males and 12 females) were 59 or older, and twenty subjects (9 males and 11 females) were between the ages of 20 and 45. All subjects were right-handed, but were otherwise selected at random.

The non-elderly subjects were recruited from the staff and students at West Park Hospital and their friends. The elderly subjects were recruited from visitors and volunteers at the hospital, and from relatives and friends of hospital staff.

The characteristics (age, height and weight distribution) of the subject population are plotted in Figures 2.2 to 2.4. Data for the general population is also shown, where available. Note that the mean heights and weights are comparable to the values cited for the general population. The elderly subject population was somewhat smaller in stature and heavier in weight than the young group, on the average.

(3) Protocol

Testing was performed in the stairway descent condition using a right-hand handrail. Handrail cross-sectional shape, diameter, and surface texture were held constant during the experiments (circular cross-section; diameter of 44.5 mm (1.75 inches); matte-finished oak surface). Six handrail heights were tested within the range of 0.81 to 1.07 meters (32 to 42 inches) (measured above the riser). The order of testing was randomized. The initial height was used as a learning trial to allow the subjects to gain familiarity with the protocol, and was re-tested at the end of the session. The total testing time for each subject was generally 50 to 55 minutes. The protocol was repeated on separate days (or with a rest interval of 30 minutes) at slopes of 41 and 49 degrees. The order in which the two slopes were tested was randomized. Prior to each experimental session, various body dimensions were measured, for use in later data analysis.

With the handrail at the mid-range height (36 inches), each subject was instructed to select his/her preferred lateral displacement from the handrail by imagining that he/she was using the handrail while descending the mock stairway. The subject was then placed in the restraining harness and the distance from the metatarsophalangeal (MP) joints to the front of the tread was estimated. (Note: distributions of preferred lateral displacement and MP joint-tread front distance are plotted in Appendices A and B respectively.)

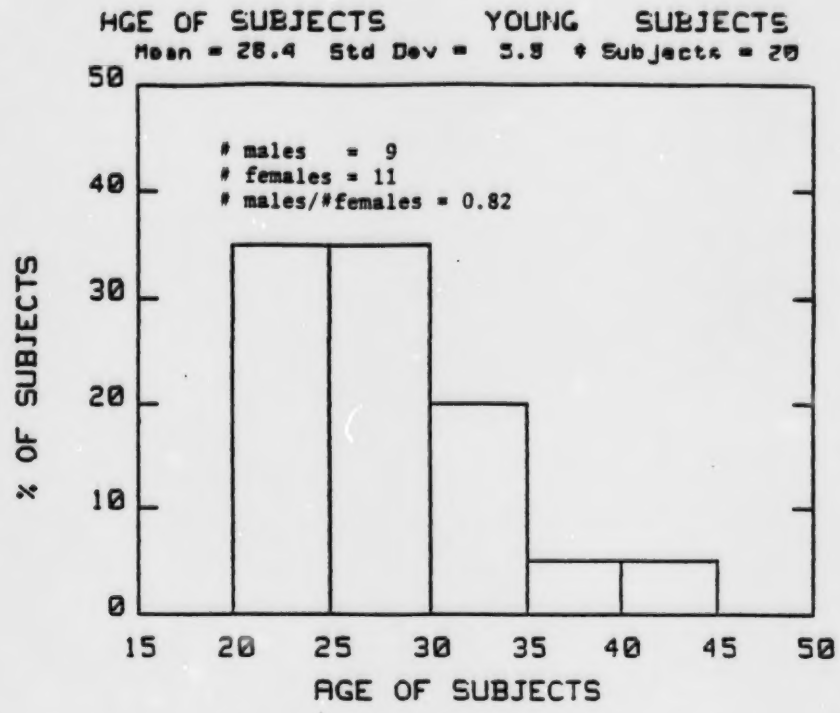


Figure 2.2 (a) Age Distribution of the Young Subjects

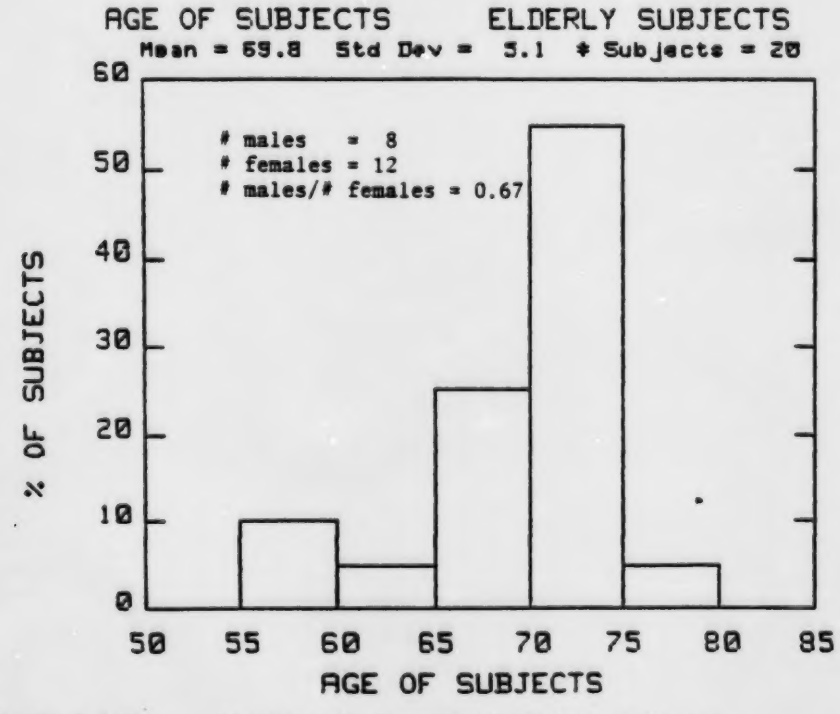


Figure 2.2 (b) Age Distribution of the Elderly Subjects

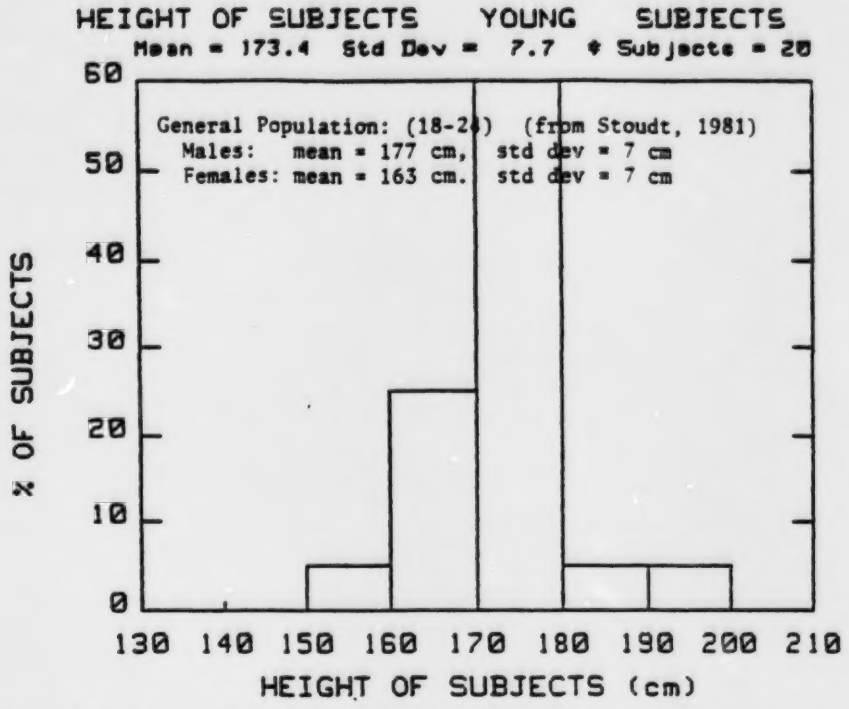

HEIGHT OF SUBJECTS YOUNG SUBJECTS
Mean = 173.4 Std Dev = 7.7 # Subjects = 20
General Population: (18-24) (from Stoudt, 1981)
Males: mean = 177 cm, std dev = 7 cm
Females: mean = 163 cm. std dev = 7 cm
% OF SUBJECTS
0
10
20
30
40
50
60
130 140 150 160 170 180 190 200 210
HEIGHT OF SUBJECTS (cm)

Figure 2.3 (a) Height Distribution of the Young Subjects

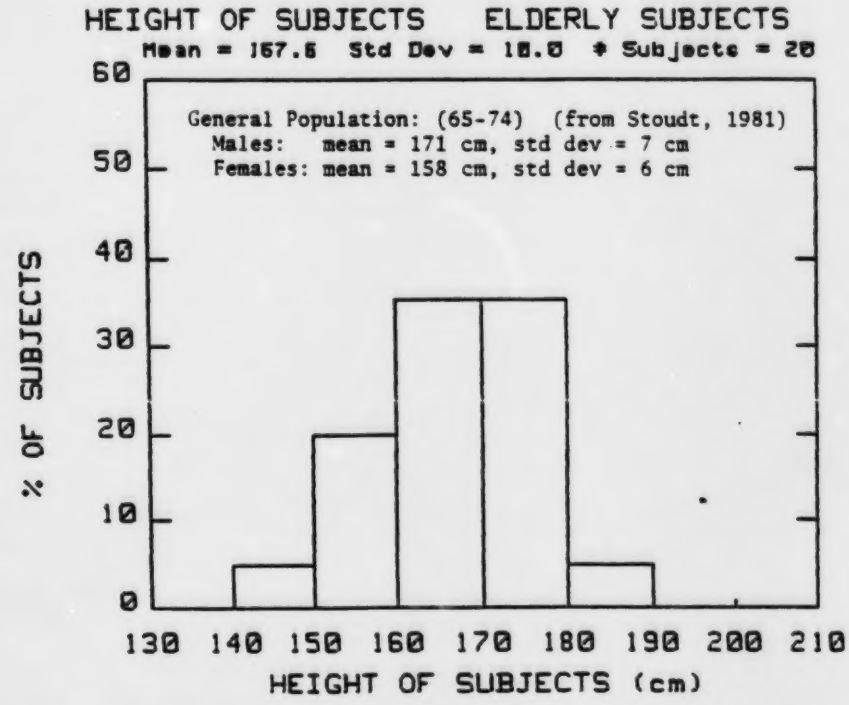

HEIGHT OF SUBJECTS ELDERLY SUBJECTS
Mean = 167.6 Std Dev = 18.0 # Subjects = 20
General Population: (65-74) (from Stoudt, 1981)
Males: mean = 171 cm, std dev = 7 cm
Females: mean = 158 cm, std dev = 6 cm
% OF SUBJECTS
0
10
20
30
40
50
60
130 140 150 160 170 180 190 200 210
HEIGHT OF SUBJECTS (cm)

Figure 2.3 (b) Height Distribution of the Elderly Subjects

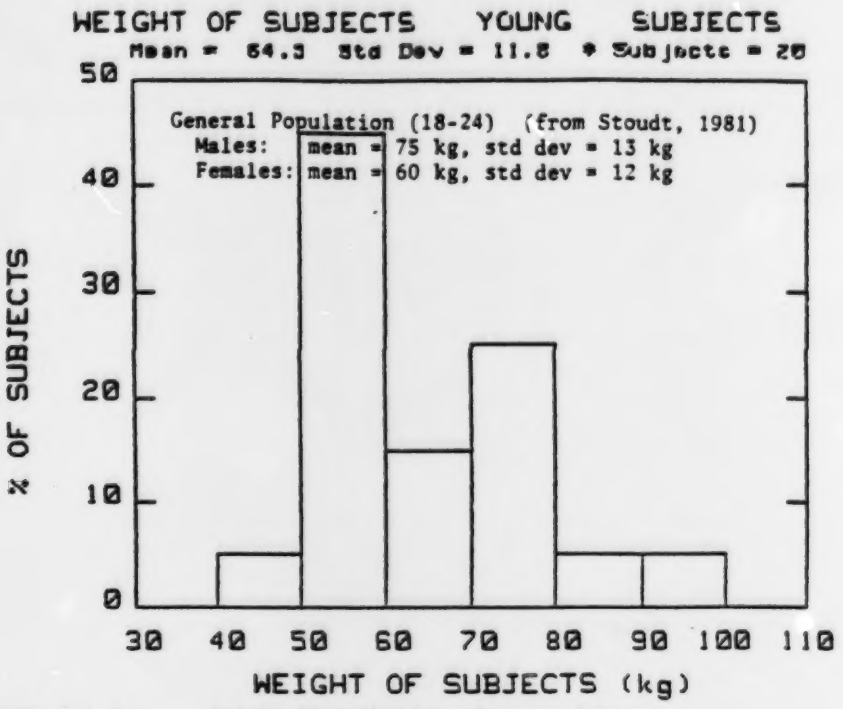

WEIGHT OF SUBJECTS YOUNG SUBJECTS
Mean = 64.3 Std Dev = 11.8 # Subjects = 20
General Population (18-24) (from Stoudt, 1981)
Males: mean = 75 kg, std dev = 13 kg
Females: mean = 60 kg, std dev = 12 kg
% OF SUBJECTS
0
10
20
30
40
50
30 40 50 60 70 80 90 100 110
WEIGHT OF SUBJECTS (kg)

Figure 2.4 (a) Weight Distribution of Young Subjects

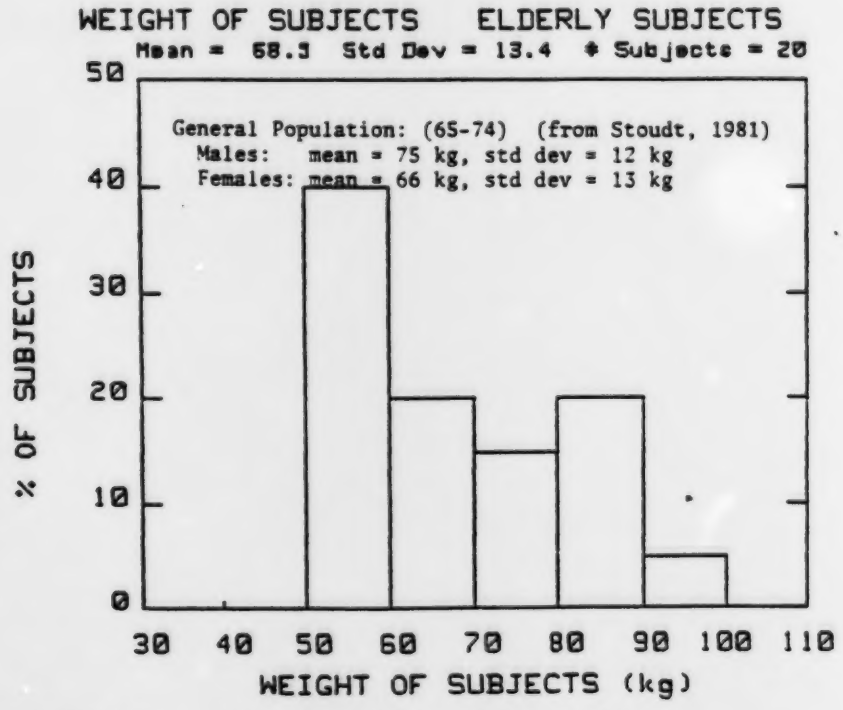

WEIGHT OF SUBJECTS ELDERLY SUBJECTS
Mean = 58.3 Std Dev = 13.4 # Subjects = 20
General Population: (65-74) (from Stoudt, 1981)
Males: mean = 75 kg, std dev = 12 kg
Females: mean = 66 kg, std dev = 13 kg
% OF SUBJECTS
0
10
20
30
40
50
30 40 50 60 70 80 90 100 110
WEIGHT OF SUBJECTS (kg)

Figure 2.4 (b) Weight Distribution of Elderly Subjects

At each handrail height, the subjects were instructed to select a grip position on the handrail by imagining that they were using the handrail while descending the mock stairway. At each handrail height, the subjects were given a sequence of four instructions: (1) "push forward along the handrail", (2) "pull backwards along the handrail", (3) "push downwards towards the ground", and (4) "pull upwards away from the ground". Subjects were instructed to start exerting the force gradually, to increase up to their maximum ability and then to relax. In order to minimize inter-subject variation, all subjects were given the same standard set of instructions. In addition, to minimize motivational variation, spectators were not allowed, and no verbal encouragements were given by the experimentor. To minimize fatigue, subjects were allowed to move their feet and arms between force measurements and were given the option of taking a rest (sitting) midway through the session.

(4) Analysis

The goals of the data analysis were as follows. For each stairway slope: (1) determine whether the ability to generate stabilizing forces and moments depends significantly on handrail height; (2) determine the nature of the relationship between handrail height and force/moment generation; (3) determine whether there are significant age-related differences in either the ability to generate stabilizing forces and moments or in the dependence of this ability on handrail height; and (4) estimate a range of acceptable handrail heights for use in building design.

The performance of each subject was characterized by the maximal force and moment that he/she was able to generate at each handrail height. To show the relationship to the different types of falling motion, the components of the forces and moments (acting on the body) were analyzed separately, to yield the five parameters listed below. Note that the variable names listed in brackets are used throughout the remainder of this report in referring to the five force and moment components. The five parameters were:

1. maximum backward moment (Mb) (counteracts forward rotation)
2. maximum forward moment (Mf) (counteracts backward rotation)
3. maximum upward force (Fu) (counteracts downward translation)
4. maximum backward force (Fb) (counteracts forward translation)
5. maximum forward force (Ff) (counteracts backward translation)

The two moments (Mb and Mf) were calculated about an axis passing through the metatarsophalangeal joints of the feet. This axis was selected as an approximation of the axis of rotation of the body during the initial stages of a fall.

To eliminate intention tremor as well as other sources of noise, the raw data was passed through a twelfth-order, zero phase-lag digital low-pass filter, with cut-off at 1 Hz. From the filtered data records, maximal values of the five stabilizing force and moment parameters were found for each experimental trial (i.e. each instruction). From the

four trials conducted at each handrail height, overall maximal values were selected.

Use of absolute force and moment values is meaningless in comparing different individuals, since the stabilizing effect of a given force or moment is dependent on the body weight and size of the individual. In order to compare different subjects, the force and moment parameters were normalized with respect to body weight and body weight moment respectively. (Body weight moment is defined as the product of body weight and height of the centre-of-gravity and represents the maximum value of destabilizing moment due to body weight.) Each normalized value indicates the stabilizing effect of the handrail relative to the corresponding destabilizing factor (body weight or body weight moment) for a given individual. In all discussion that follows, normalization with respect to body parameters is assumed, unless specified otherwise.

Statistical analyses were performed on the normalized force and moment data. Analysis of variance (with split plot design) was used to evaluate the effects of age and handrail height on the generation of stabilizing forces and moments. Analysis of covariance was used to investigate the nature of the relationship between handrail height and ability to generate stabilizing forces and moments. In all the analyses, the two stairway slopes were treated separately.

The analysis of covariance assumes a linear model of the form:

$$Yij = u + Ai + Bi\ Xj + Eij$$

where:

Yij = normalized force or moment of the ith subject at the jth handrail height

u = overall mean effect

Ai = y-intercept of the ith subject (minus u)

Bi = slope of the ith subject

Xj = jth handrail height

Eij = error term (due to motivational variation, measurement error, etc)

The linear model was justified by the trends evident in the data (see Figures 3.1 to 3.10). Some of the subjects appeared to have a quadratic rather than linear dependence on handrail height; however, use of a higher-order polynomial regression model showed negligible improvement over the linear fit.

For each force and moment parameter, histograms were constructed to show the percentage of subjects who were able to exceed a given level of force or moment at each handrail height. Initially, a high level was chosen such that no subjects were found to attain it. The level was then successively decreased until at least 75% of the subjects were found to exceed that level at a minimum of four handrail heights. These heights were deemed to be "acceptable". This procedure was repeated for all five force and moment parameters. An "optimal" range of handrail heights was then defined as those heights that were "acceptable" in all five cases. Note that each parameter was analyzed separately, and that each age group was analyzed separately.

III RESULTS

The data for the 41-degree slope is plotted in Figures 3.1 to 3.5, while the data for the 49-degree slope is plotted in Figures 3.6 to 3.10. Each plot represents the variation of a given normalized force or moment with handrail height. The result for each subject is plotted separately to allow trends to be identified. To facilitate comparison, results for the young and the elderly subjects have been plotted on separate graphs.

(1) Effect of Handrail Height

(i) Difference between Means

The results of the analysis of variance are summarized in Tables 3.1 and 3.2. Each slope was analyzed separately, and for each slope, the analysis of the five normalized force and moment parameters was performed separately. For each of the five parameters, the mean parameter value was calculated at each of the six handrail heights, using all of the subjects. Associated 95% confidence limits were also calculated for each mean.

The null hypothesis states that the means at the different handrail heights are equal. The levels of significance indicated in the tables refer to the test of the null hypothesis. Small levels of significance imply that the null hypothesis is incorrect, namely, that there <u>is</u> a significant difference between the means.

It is evident from the results shown in the tables that the differences between the means are highly significant (at p=.05 for Fb at the 49-degree slope, at p=.01 in all other cases) for both stairway slopes. Thus, we conclude that <u>handrail height has a highly significant effect on the ability to generate certain stabilizing forces and moments</u>.

Note that for parameters Mb, Mf, Fb (at the 41-degree slope) and Ff, the mean values increase with increasing handrail height. For parameter Fu (vertical force), the mean values tend to decrease with increasing handrail height. These trends are also evident in the "raw" data (Figures 3.1 to 3.10).

(ii) Linear Dependence

The nature of the relationship between the parameter values and handrail height was evaluated using analysis of covariance. The results of the analysis are summarized in Tables 3.3 and 3.4.

For each parameter, the correlation coefficient was calculated, assuming: (1) a single common slope for all subjects, and (2) separate

TABLE 3.1 - Effect of Handrail Height (Slope = 41 degrees)

	Handrail Height	Mean	95% Confidence Interval	
Parameter Mb	32"	0.110	0.105	0.115
	34"	0.125	0.120	0.129
(Backward	36"	0.140	0.135	0.144
Moment)	38"	0.153	0.148	0.158
	40"	0.163	0.159	0.168
	42"	0.178	0.173	0.183
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Mf	32"	0.123	0.118	0.129
	34"	0.153	0.147	0.158
(Forward	36"	0.180	0.175	0.186
Moment)	38"	0.201	0.196	0.207
	40"	0.224	0.218	0.229
	42"	0.235	0.230	0.241
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Fb	32"	0.100	0.097	0.103
	34"	0.103	0.100	0.106
(Backward	36"	0.105	0.101	0.108
Force)	38"	0.108	0.105	0.111
	40"	0.109	0.106	0.112
	42"	0.112	0.109	0.115
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Ff	32"	0.111	0.106	0.117
	34"	0.126	0.120	0.131
(Forward	36"	0.140	0.134	0.145
Force)	38"	0.148	0.142	0.154
	40"	0.159	0.154	0.165
	42"	0.161	0.156	0.167
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Fu	32"	0.259	0.253	0.264
	34"	0.254	0.249	0.259
(Upward	36"	0.254	0.249	0.260
Force)	38"	0.253	0.248	0.259
	40"	0.245	0.240	0.251
	42"	0.225	0.220	0.231
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			

TABLE 3.2 - Effect of Handrail Height (Slope = 49 degrees)

	Handrail Height	Mean	95% Confidence Interval	
Parameter Mb	32"	0.089	0.085	0.092
	34"	0.095	0.091	0.099
(Backward	36"	0.112	0.108	0.116
Moment)	38"	0.120	0.116	0.124
	40"	0.135	0.131	0.139
	42"	0.135	0.131	0.139
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Mf	32"	0.100	0.095	0.105
	34"	0.127	0.121	0.132
(Forward	36"	0.156	0.151	0.161
Moment)	38"	0.179	0.174	0.185
	40"	0.199	0.193	0.204
	42"	0.212	0.206	0.217
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Fb	32"	0.082	0.079	0.085
	34"	0.077	0.075	0.080
(Backward	36"	0.086	0.082	0.087
Force)	38"	0.082	0.079	0.085
	40"	0.086	0.083	0.089
	42"	0.082	0.079	0.085
	Level of significance: $p < .05$			
	Conclusion: significant difference between means			
Parameter Ff	32"	0.093	0.089	0.097
	34"	0.107	0.103	0.110
(Forward	36"	0.122	0.118	0.126
Force)	38"	0.133	0.130	0.137
	40"	0.141	0.137	0.145
	42"	0.146	0.142	0.150
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Fu	32"	0.266	0.261	0.272
	34"	0.254	0.249	0.260
(Upward	36"	0.264	0.258	0.270
Force)	38"	0.257	0.251	0.263
	40"	0.249	0.243	0.254
	42"	0.245	0.239	0.250
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			

TABLE 3.3 - Linear Dependence on Handrail Height
(Slope = 41 degrees)

	Mb Backward Moment	Mf Forward Moment	Fb Backward Force	Ff Forward Force	Fu Upward Force
ALL SUBJECTS					
Correlation Coefficient (R)	0.899	0.894	0.919	0.908	-0.915
Pooled Slope (B) *	0.0139	0.0233	0.0267	0.0107	-0.0048
Test for Common Slope (p) **	$.01<p<.05$	$p < .01$	$p > .05$	$.01<p<.05$	$p > .05$
YOUNG SUBJECTS					
Correlation Coefficient (R)	0.861	0.846	0.879	0.838	-0.838
Pooled Slope (B) *	0.0182	0.0295	0.0037	0.0131	-0.0069
Test for Common Slope (p) **	$p > .05$	$p > .05$	$p > .05$	$p > .05$	$p > .05$
ELDERLY SUBJECTS					
Correlation Coefficient (R)	0.921	0.942	0.907	0.942	-0.883
Pooled Slope (B) *	0.0096	0.0170	0.0016	0.0083	-0.0028
Test for Common Slope (p) **	$p > .05$	$p < .01$	$p > .05$	$p \simeq .05$	$p > .05$

Note: * slope = change in normalized parameter per unit change in handrail height (in inches)

** Null Hypothesis (Ho): the subjects have a common slope.
Therefore: reject Ho if $p < .01$
accept Ho if $p > .05$

TABLE 3.4 - Linear Dependence on Handrail Height
(Slope = 49 degrees)

	Mb Backward Moment	Mf Forward Moment	Fb Backward Force	Ff Forward Force	Fu Upward Force
ALL SUBJECTS					
Correlation Coefficient (R)	0.953	0.928	0.959	0.928	-0.935
Pooled Slope (B) *	0.0105	0.0233	0.0008	0.0113	-0.0035
Test for Common Slope (p) **	$p \simeq .05$	$p < .01$	$p < .01$	$p \simeq .05$	$p > .05$
YOUNG SUBJECTS					
Correlation Coefficient (R)	0.936	0.933	0.938	0.909	-0.884
Pooled Slope (B) *	0.0115	0.0308	0.0008	0.0149	-0.0063
Test for Common Slope (p) **	$p > .05$	$p < .01$	$p < .01$	$p > .05$	$p > .05$
ELDERLY SUBJECTS					
Correlation Coefficient (R)	0.946	0.902	0.931	0.885	-0.879
Pooled Slope (B) *	0.0096	0.0157	0.0019	0.0075	-0.0006
Test for Common Slope (p) **	$p > .05$	$p > .05$	$p > .05$	$p > .05$	$p > .05$

Note: * slope = change in normalized parameter per unit change in handrail height (in inches)

** Null Hypothesis (Ho): the subjects have a common slope.
Therefore: reject Ho if $p < .01$
accept Ho if $p > .05$

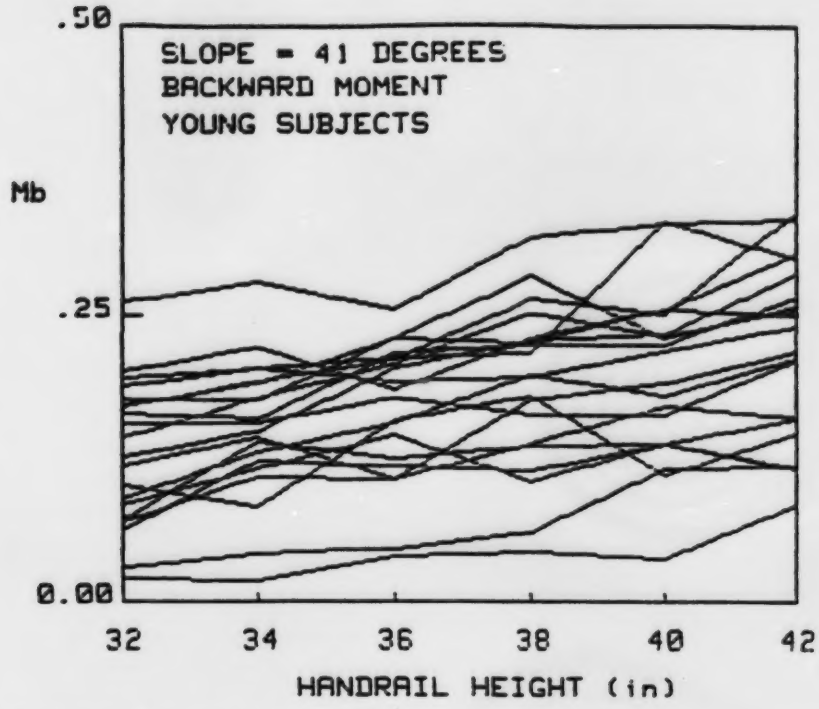


Figure 3.1 (a) Mb versus Handrail Height, Slope = 41 degrees, Young Subjects (Mb = maximum backward moment/body weight moment)

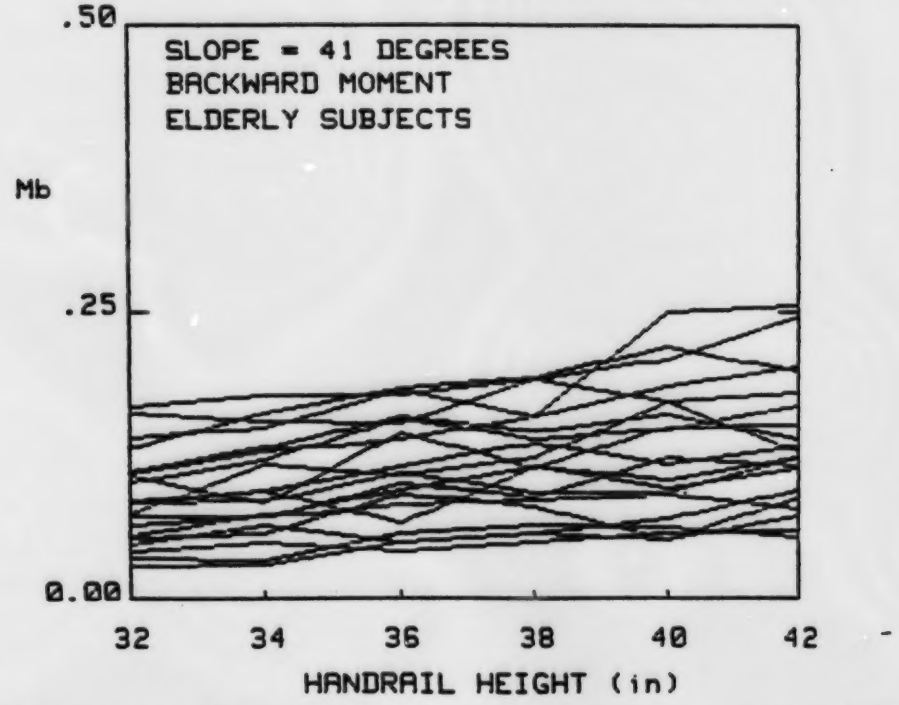


Figure 3.1 (b) Mb versus Handrail Height, Slope = 41 degrees, Elderly Subject (Mb = maximum backward moment/body weight moment)

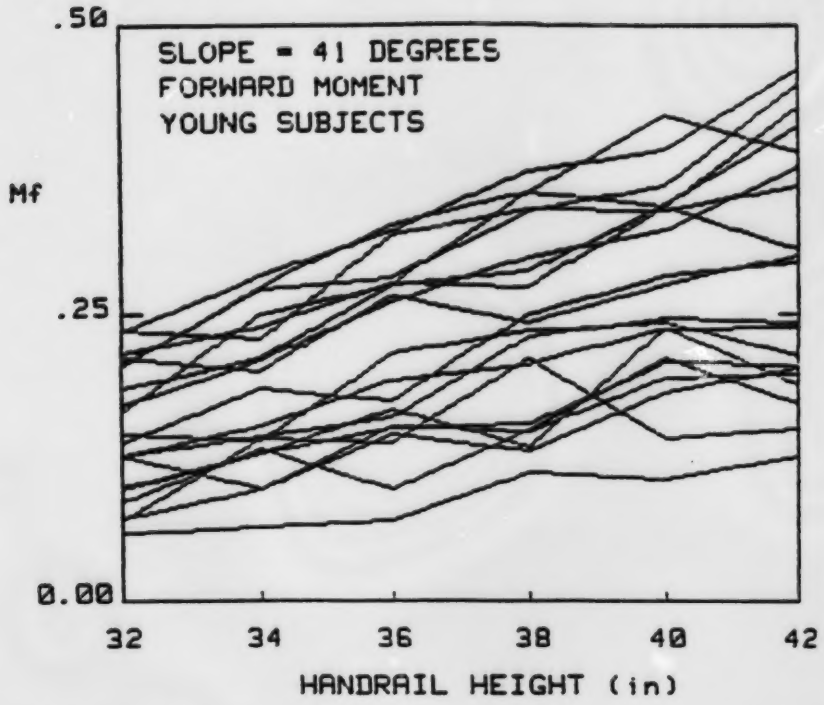


Figure 3.2 (a) Mf versus Handrail Height, Slope = 41 degrees, Young Subjects
(Mf = maximum forward moment/body weight moment)

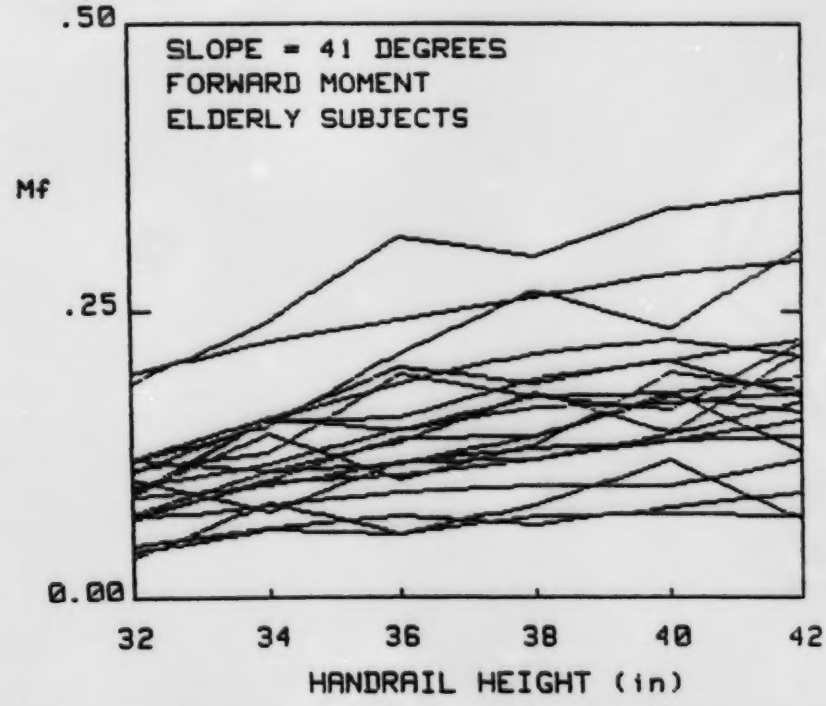


Figure 3.2 (b) Mf versus Handrail Height, Slope = 41 degrees, Elderly Subjects
(Mf = maximum forward moment/body weight moment)

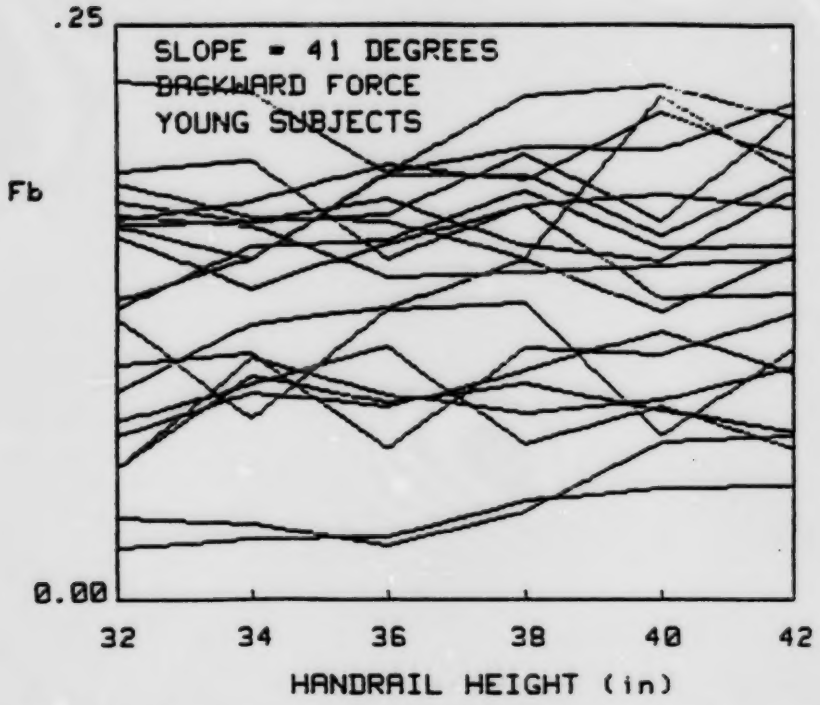


Figure 3.3 (a) Fb versus Handrail Height, Slope = 41 degrees, Young Subjects (Fb = maximum backward force/body weight)

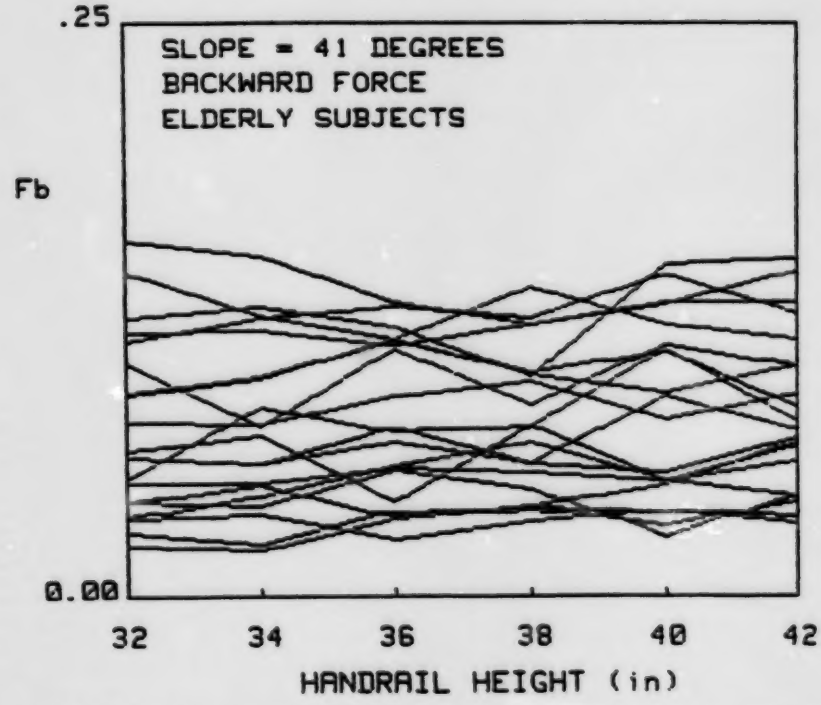


Figure 3.3 (b) Fb versus Handrail Height, Slope = 41 degrees, Elderly Subjects (Fb = maximum backward force/body weight)

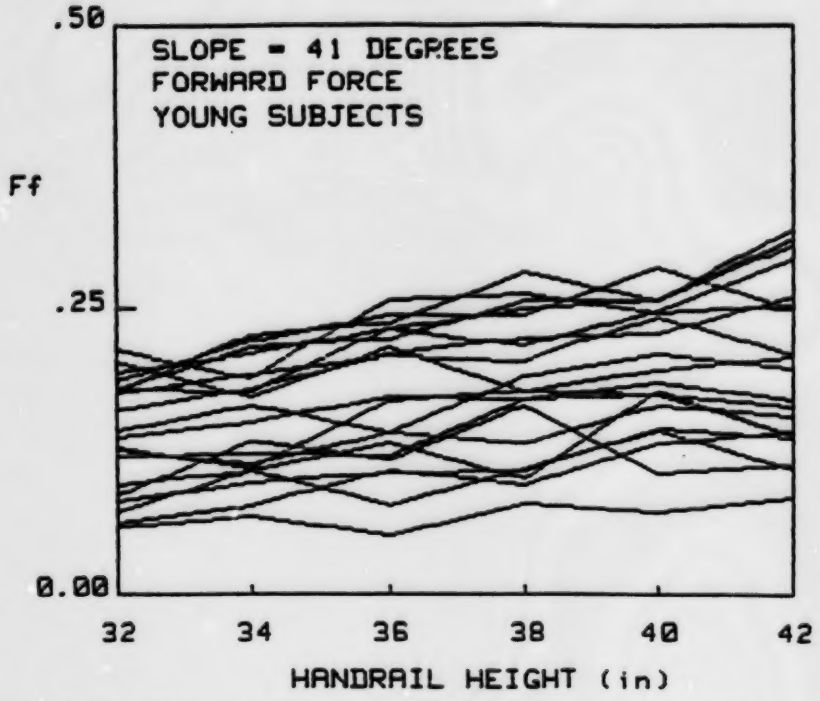


Figure 3.4 (a) Ff versus Handrail Height, Slope = 41 degrees, Young Subjects (Ff = maximum forward force/body weight)

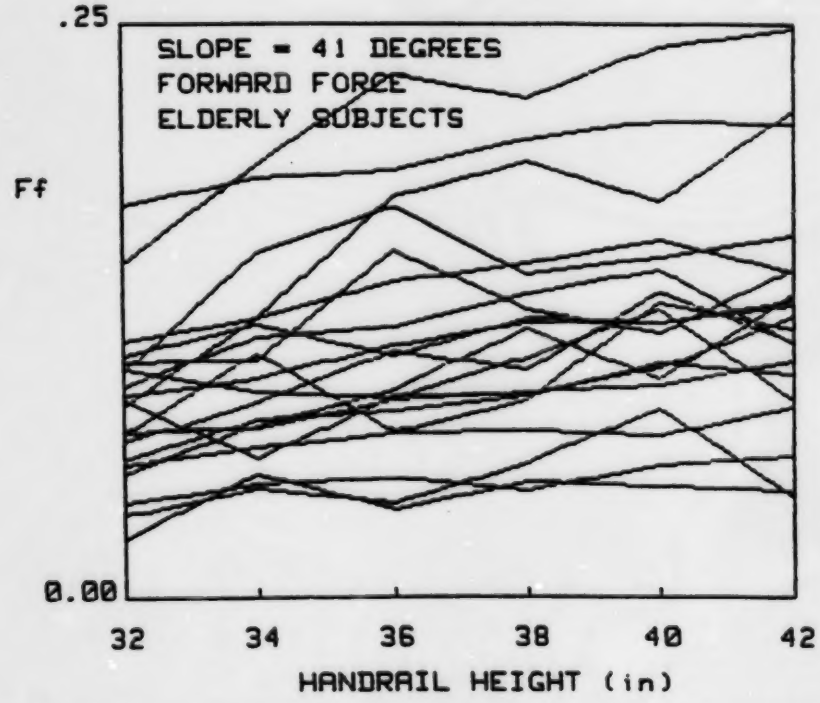


Figure 3.4 (b) Ff versus Handrail Height, Slope = 41 degrees, Elderly Subjects (Ff = maximum forward force/body weight)

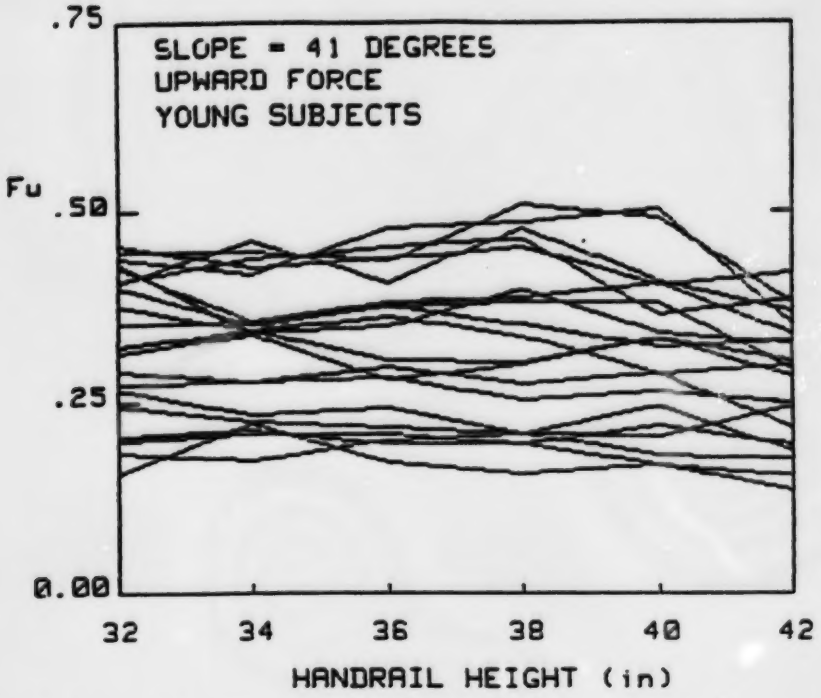


Figure 3.5 (a) Fu versus Handrail Height, Slope = 41 degrees, Young Subjects (Fu = maximum upward force/body weight)

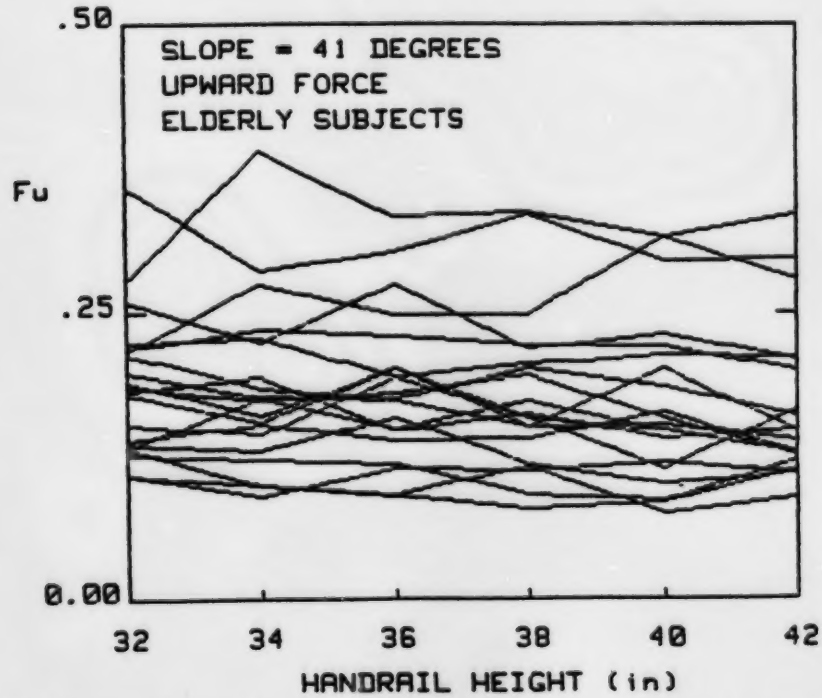


Figure 3.5 (b) Fu versus Handrail Height, Slope = 41 degrees, Elderly Subjects (Fu = maximum upward force/body weight)

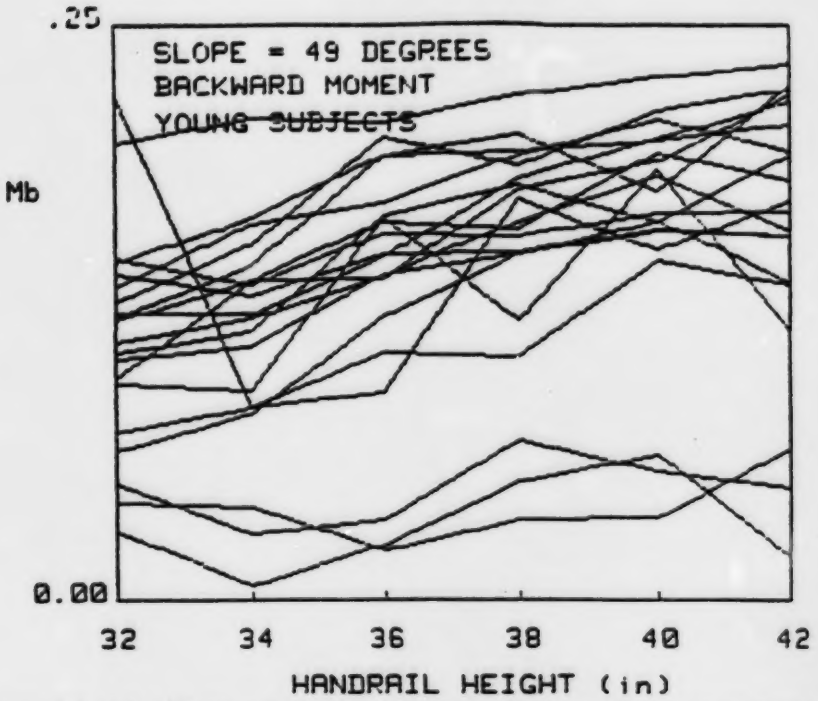


Figure 3.6 (a) Mb versus Handrail Height, Slope = 49 degrees, Young Subjects (Mb = maximum backward moment/body weight moment)

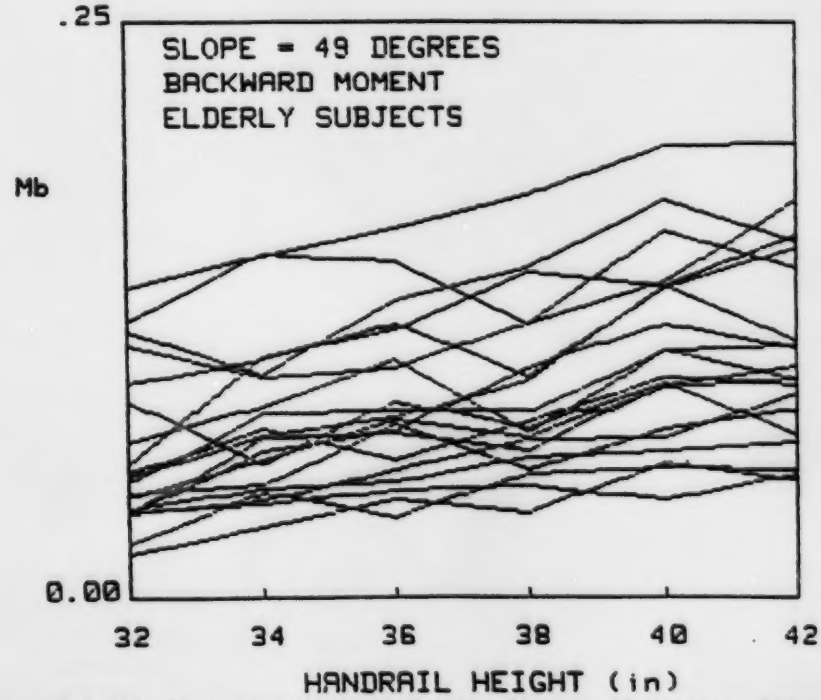


Figure 3.6 (b) Mb versus Handrail Height, Slope = 49 degrees, Elderly Subjects (mb = maximum backward moment.body weight moment)

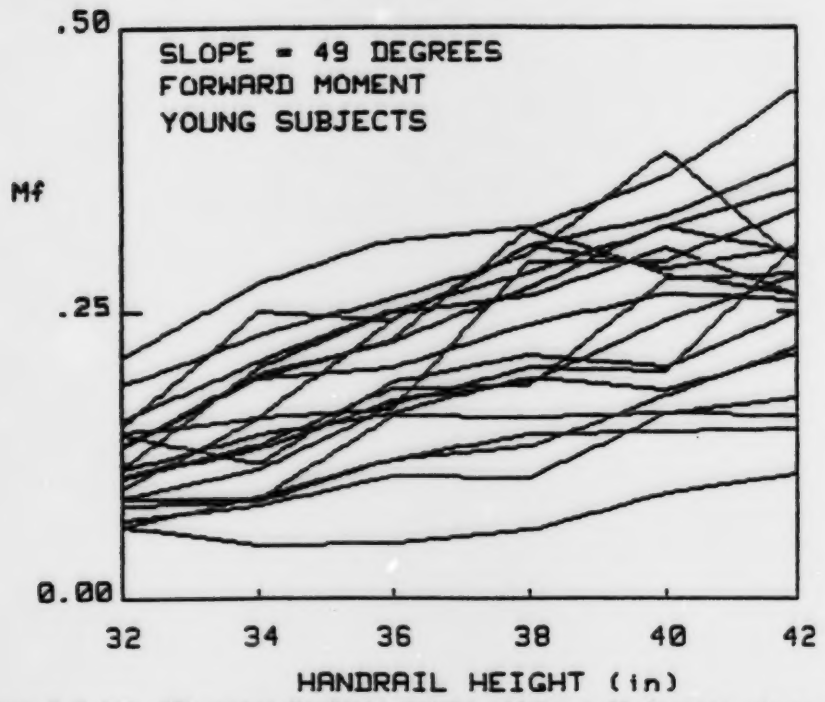


Figure 3.7 (a) Mf versus Handrail Height, Slope = 49 degrees, Young Subjects (Mf = maximum forward moment/body weight moment).

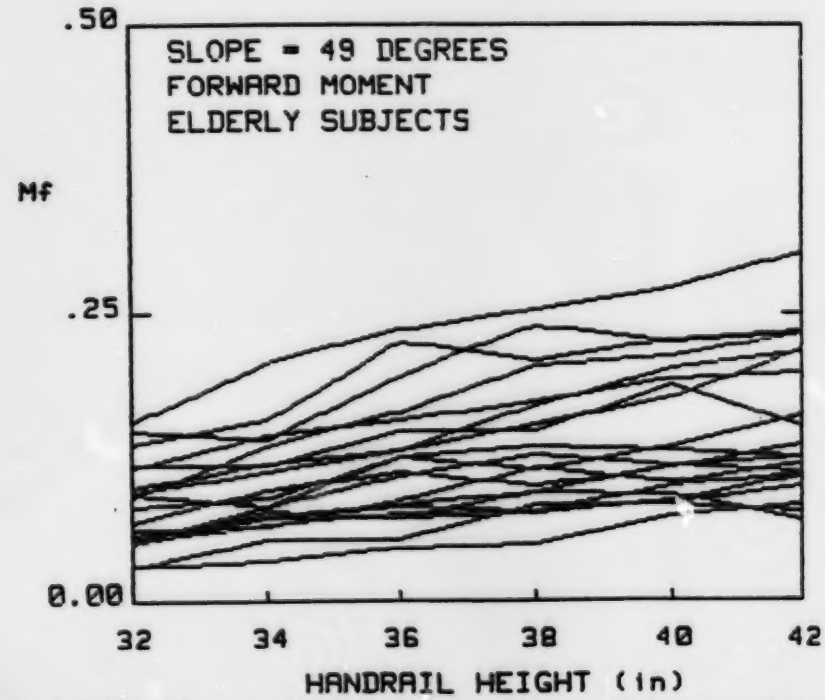


Figure 3.7 (b) Mf versus Handrail Height, Slope = 49 degrees, Elderly Subjects (Mf = maximum forward moment/body weight moment)

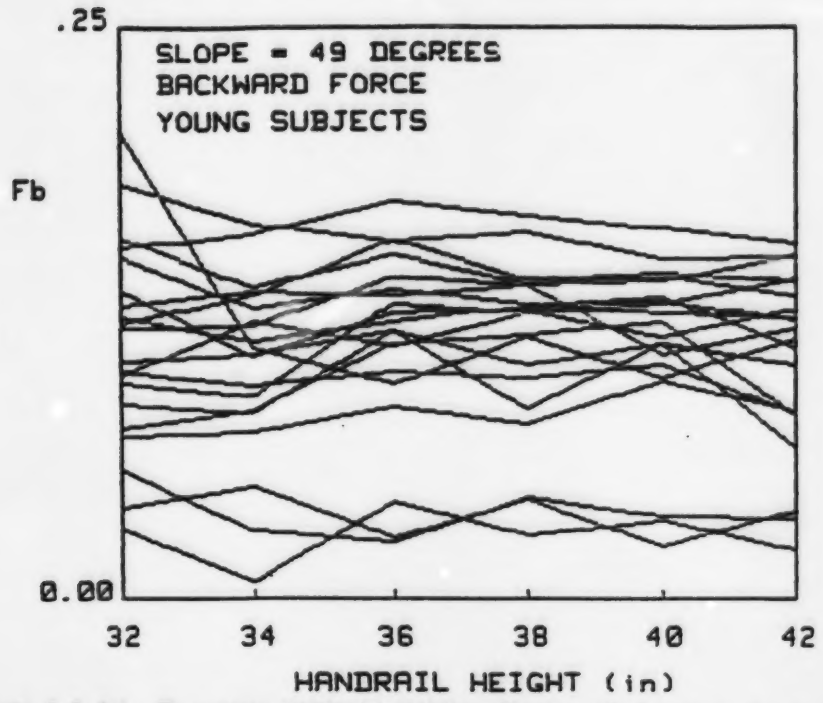


Figure 3.8 (a) Fb versus Handrail Height, Slope = 49 degrees, Young Subjects (Fb = maximum backward force/body weight)

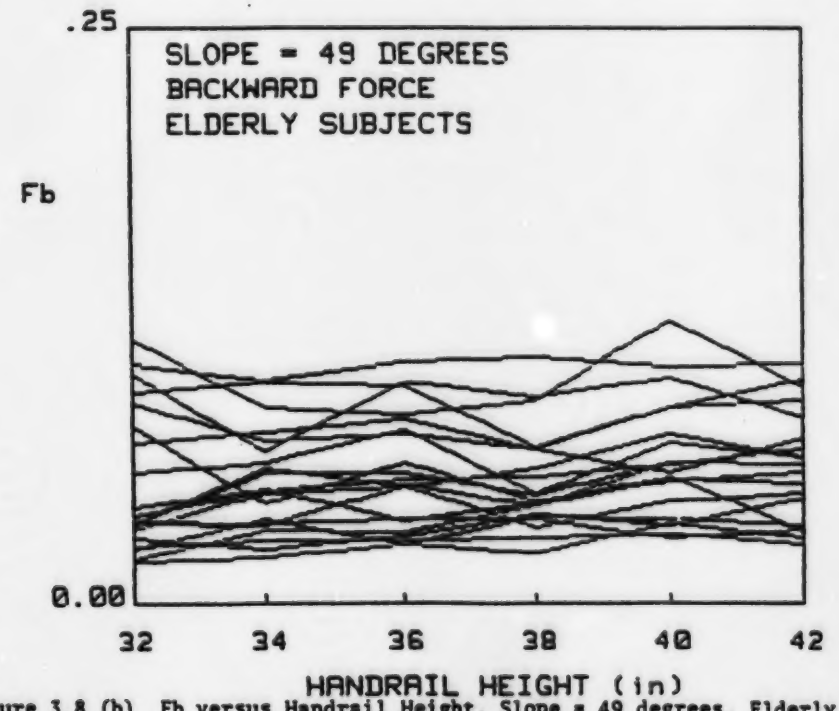


Figure 3.8 (b) Fb versus Handrail Height, Slope = 49 degrees, Elderly Subjects (Fb = maximum backward force/body weight)

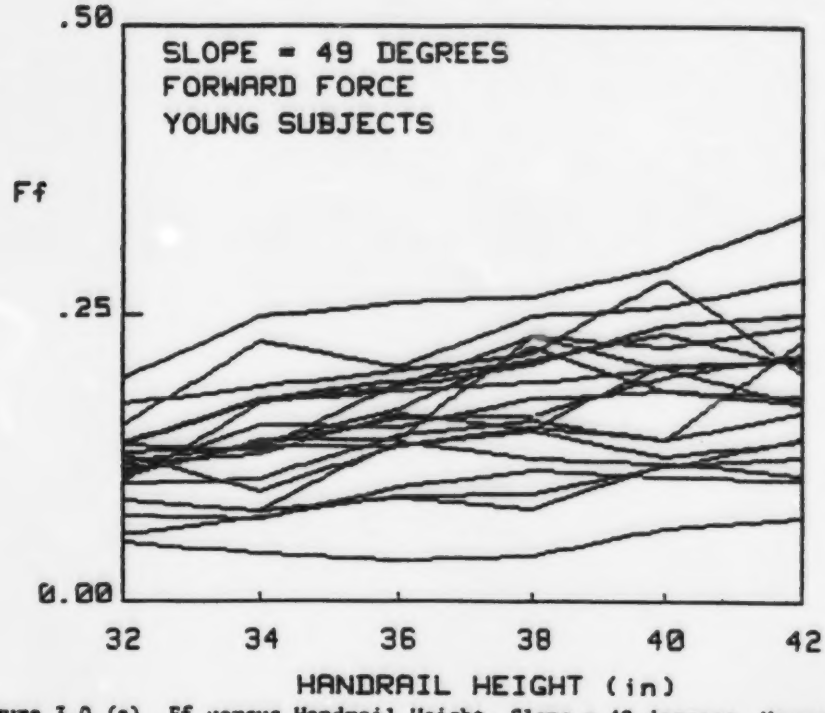


Figure 3.9 (a) Ff versus Handrail Height, Slope = 49 degrees, Young Subjects
(Ff = maximum forward force/body weight)

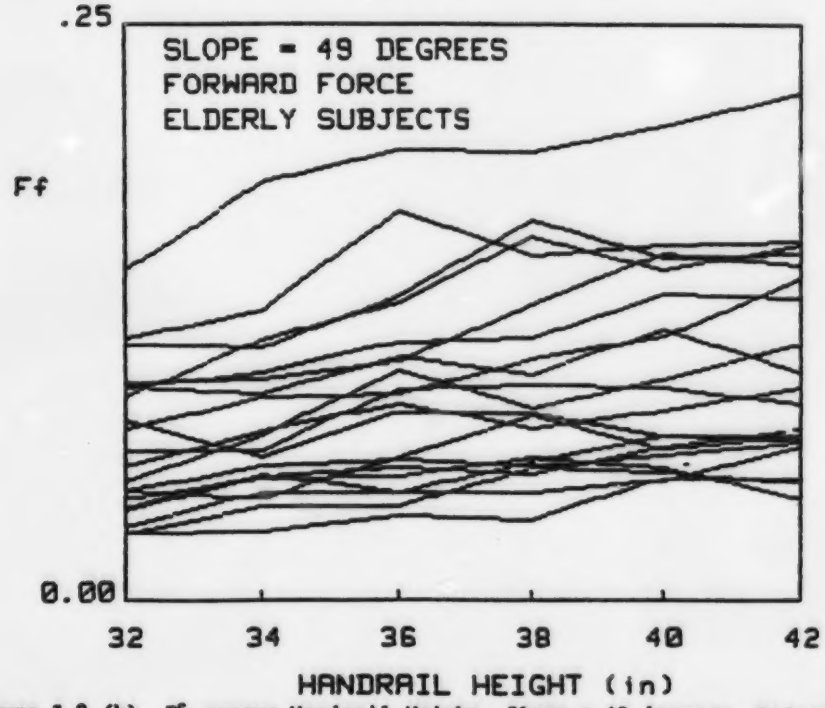


Figure 3.9 (b) Ff versus Handrail Height, Slope = 49 degrees, Elderly Subjects
(Ff = maximum forward force/body weight)

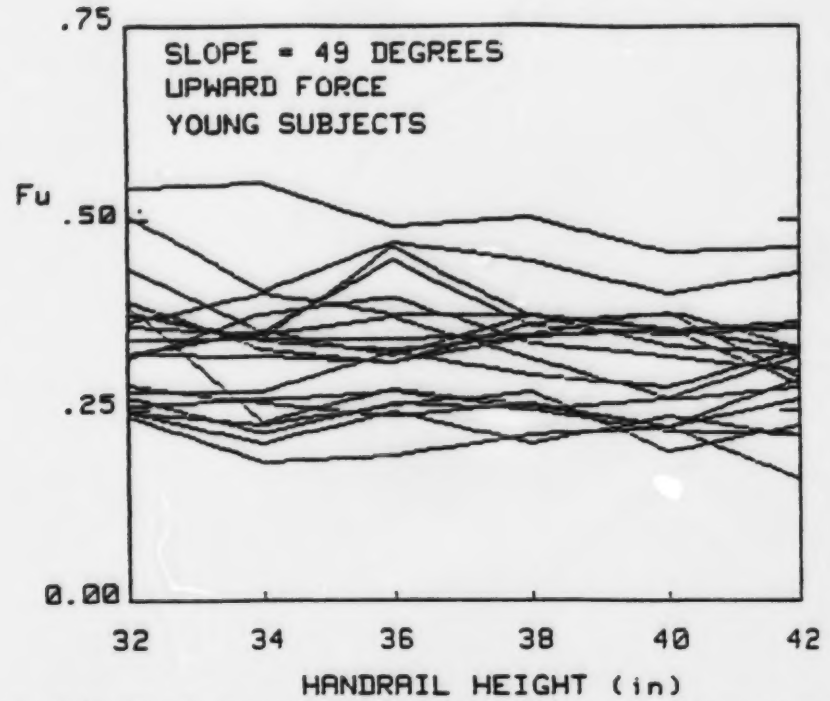


Figure 3.10 (a) Fu versus Handrail Height, Slope = 49 degrees, Young Subjects
(Fu = maximum upward force/body weight)

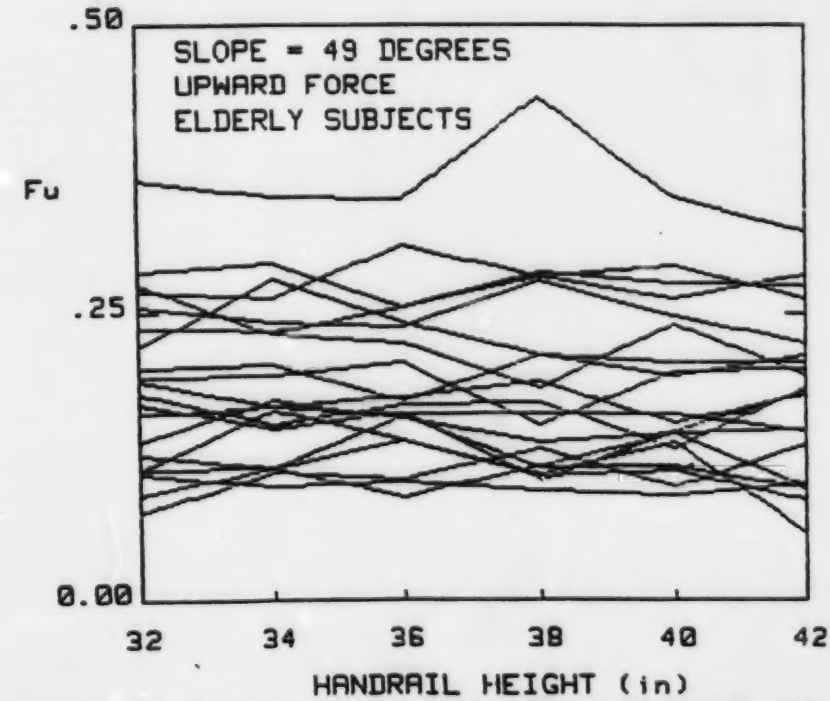


Figure 3.10 (b) Fu versus Handrail Height, Slope = 49 degrees, Elderly Subjects
(Fu = maximum upward force/body weight)

common slopes for the two age groups. As shown in the tables, all five parameters had correlation coefficients with absolute values greater than or equal to 0.84, at both stairway slopes. This implies that the linear model fits the data well; therefore, we conclude that there is a strong linear relationship between ability to generate stabilizing forces/moments and handrail height.

The positive correlation coefficients obtained for parameters Mf, Mb, Ff and Fb indicate that these parameters increase with increasing handrail height. The negative value obtained for Fu indicates that this parameter (vertical force) decreases with increasing handrail height.

The pooled (common) slope was also calculated for each parameter. Recall that the slope is a measure of the linear dependence of force or moment generation on handrail height. Quantitatively, these values indicate the change in the normalized parameter value per unit change in handrail height (in inches). Note that the pooled slopes are all positive for parameters Mb, Mf, Ff and Fb, but negative for parameter Fu, thereby confirming the trends mentioned earlier.

It is evident from the plots (Figures 3.1 to 3.10) that while many subjects in each age group had approximately equal slopes, the y-intercepts were substantially different. The analysis of covariance tested both of these hypotheses. In addition, given equal slopes, it allowed us to check that the common slope was not zero, which would imply no dependence of force/moment generation on handrail height.

The hypothesis that all subjects in each age group have a common slope was accepted (at p=0.05) in most cases. The exceptions were Mf (for the elderly at 41-degrees and the young at 49-degrees) and Fb (for the young at 49-degrees). The hypothesis that all subjects (regardless of age group) have the same slope was tested, but the results generally did not show a common slope, except for parameter Fu (at both stairway slopes) and for parameter Fb (at the 41-degree stairway slope).

The hypothesis that the common slope is zero was found to be incorrect (at p=0.01) in all cases where there was a common slope. Thus, the earlier findings of a common slope are indicative of a significant dependence of the parameters on handrail height. The hypothesis that all subjects have equal y-intercepts was found to be incorrect (at p=0.01) in all cases. This confirms the earlier qualitative finding.

(2) Age Differences

(i) Difference between Means

The results of the analysis of variance (split plot design) pertaining to age are listed in Tables 3.5 and 3.6. For each stairway slope and parameter, mean values were calculated for each age group,

TABLE 3.5 - Effect of Age (Slope = 41 degrees)

	Age Group	Mean	95% Confidence Interval	
Parameter Mb				
(Backward Moment)	Young	0.175	0.171	0.179
	Elderly	0.114	0.110	0.118
	Level of significance: $p < .01$ Conclusion: significant difference between means			
Parameter Mf				
(Forward Moment)	Young	0.224	0.219	0.228
	Elderly	0.149	0.144	0.161
	Level of significance: $p < .01$ Conclusion: significant difference between means			
Parameter Fb				
(Backward Force)	Young	0.133	0.130	0.136
	Elderly	0.079	0.076	0.081
	Level of significance: $p < .01$ Conclusion: significant difference between means			
Parameter Ff				
(Forward Force)	Young	0.173	0.169	0.176
	Elderly	0.109	0.106	0.112
	Level of significance: $p < .01$ Conclusion: significant difference between means			
Parameter Fu				
(Upward Force)	Young	0.318	0.305	0.322
	Elderly	0.179	0.175	0.183
	Level of significance: $p < .01$ Conclusion: significant difference between means			

TABLE 3.6 - Effect of Age (Slope = 49 degrees)

	Age Group	Mean	95% Confidence Interval	
Parameter Mb				
(Backward Moment)	Young	0.141	0.138	0.144
	Elderly	0.088	0.085	0.091
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Mf				
(Forward Moment)	Young	0.201	0.197	0.206
	Elderly	0.123	0.119	0.127
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Fb				
(Backward Force)	Young	0.108	0.106	0.110
	Elderly	0.057	0.054	0.059
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Ff				
(Forward Force)	Young	0.158	0.155	0.161
	Elderly	0.089	0.086	0.092
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			
Parameter Fu				
(Upward Force)	Young	0.324	0.319	0.329
	Elderly	0.188	0.183	0.192
	Level of significance: $p < .01$			
	Conclusion: significant difference between means			

based on results at all six handrail heights. Associated 95% confidence levels were also calculated for each mean.

The null hypothesis states that the means of the two age groups are equal. Small levels of significance indicate that the hypothesis is incorrect and that the means are in fact significantly different. As shown in the tables, the results imply that there are significant age differences in ability to generate stabilizing forces and moments.

Examination of the data in the tables shows that the mean values of the young subjects are higher than those of the elderly subjects.

(ii) Interaction between Age and Handrail Height

The interaction between age and handrail height is shown in Tables 3.7 and 3.8. Significant interaction means that the nature of the dependence of force/moment generation on handrail height is different for the two age groups. For a linear dependence (as was found to exist here), this means that the two age groups should have different slopes.

The null hypothesis is that there is no significant interaction; therefore, small levels of significance indicate that the hypothesis is wrong and that there is significant interaction. The results listed in the tables indicate significant interaction (at p=.05) for all parameters except Fb.

The analysis of covariance found that the slopes of the two age groups were significantly different (at p=.01) for Mf and Ff (at both stairway slopes) and for Mb (at the 41-degree stairway slope). In each of these cases, the slope of the elderly subjects was smaller.

(3) Estimation of an Optimal Design Range for Handrail Height

The design histograms are plotted in Figures 3.11 to 3.15 (slope of 41 degrees) and Figures 3.16 to 3.20 (slope of 49 degrees). These histograms show the percentage of subjects who were able to generate "acceptable" force or moment levels versus handrail height. Note that the two slopes are analyzed separately. At each slope, each parameter is analyzed separately, and each age group is analyzed separately.

For each parameter (and for each age group), a range of acceptable handrail heights is derived in the manner described earlier. These results are listed in Table 3.9. For completeness, the results of the previous study (slope of 33 degrees) are also listed in Table 3.9.

For parameter Fb, all of the tested heights appear to be satisfactory, at the 49-degree slope. The same is true of Fb and Ff for the elderly subjects at the 33-degree slope. In all other cases, analyses of parameters Mb, Mf, Fb and Ff all point to lower limits on handrail height. This is to be expected, since the earlier analysis

TABLE 3.7 - Interaction of Age and Handrail Height
(Slope = 41 degrees)

Parameter Mb - Backward Moment

Level of significance: $p < .01$
Conclusion: significant interaction

Parameter Mf - Forward Moment

Level of significance: $p < .01$
Conclusion: significant interaction

Parameter Fb - Backward Force

Level of significance: $p > .05$
Conclusion: no significant interaction

Parameter Ff - Forward Force

Level of significance: $p < .05$
Conclusion: significant interaction

Parameter Fu - Upward Force

Level of significance: $p < .05$
Conclusion: significant interaction

TABLE 3.8 - Interaction of Age and Handrail Height
(Slope = 49 degrees)

Parameter Mb - Backward Moment

Level of significance: $p < .05$
Conclusion: significant interaction

Parameter Mf - Forward Moment

Level of significance: $p < .01$
Conclusion: significant interaction

Parameter Fb - Backward Force

Level of significance: $p > .05$
Conclusion: no significant interaction

Parameter Ff - Forward Force

Level of significance: $p < .01$
Conclusion: significant interaction

Parameter Fu - Upward Force

Level of significance: $p < .01$
Conclusion: significant interaction

TABLE 3.9 - Summary of Design Estimates

PARAMETER	ACCEPTABLE RANGE OF HANDRAIL HEIGHTS	
	YOUNG SUBJECTS	ELDERLY SUBJECTS
SLOPE = 33 DEGREES		
Mb - Backward Moment	height ≥ 36"	height ≥ 36"
Mf - Forward Moment	height ≥ 36"	height ≥ 34"
Fb - Backward Force	height ≥ 34"	any height tested
Ff - Forward Force	height ≥ 36"	any height tested
Fu - Upward Force	height ≤ 38"	height ≤ 40" *
Overall	36" ≤ height ≤ 38"	36" ≤ height ≤ 40"
SLOPE = 41 DEGREES		
Mb - Backward Moment	height ≥ 34"	height ≥ 36"
Mf - Forward Moment	height ≥ 36"	height ≥ 36"
Fb - Backward Force	height ≥ 34"	height ≥ 36"
Ff - Forward Force	height ≥ 36"	height ≥ 36"
Fu - Upward Force	any height tested	height ≤ 38"
Overall	height ≥ 36"	36" ≤ height ≤ 38"
SLOPE = 49 DEGREES		
Mb - Backward Moment	height ≥ 36"	height ≥ 36"
Mf - Forward Moment	height ≥ 36"	height ≥ 36"
Fb - Backward Force	any height tested	any height tested
Ff - Forward Force	height ≥ 36"	height ≥ 34"
Fu - Upward Force	any height tested	any height tested
Overall	height ≥ 36"	height ≥ 36"

* Note: discontinuity at height = 38" judged to be insignificant.

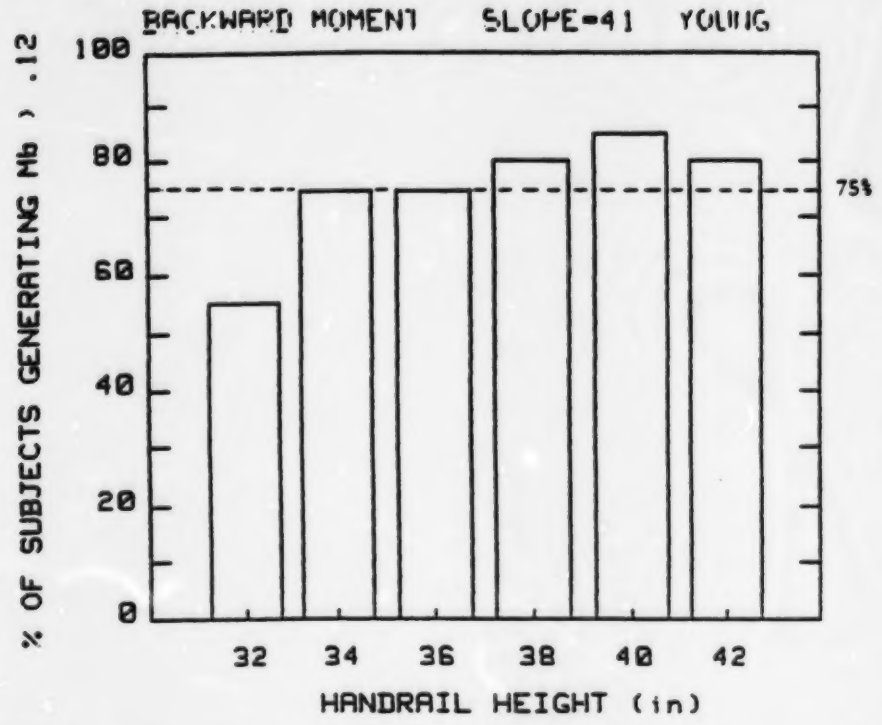


Figure 3.11 (a) Design Range Inferred from Mb, Slope = 41 degrees, Young Subjects
(Mb = maximum backward moment/body weight moment)

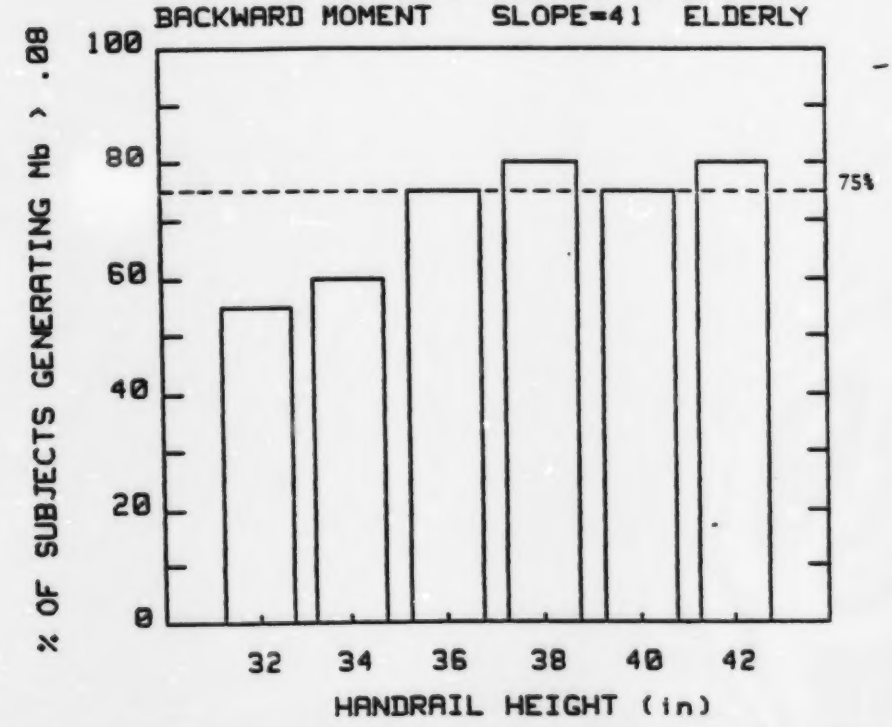


Figure 3.11 (b) Design Range Inferred from Mb, Slope = 41 deg, Elderly Subjects
(Mb = maximum backward moment/body weight moment)

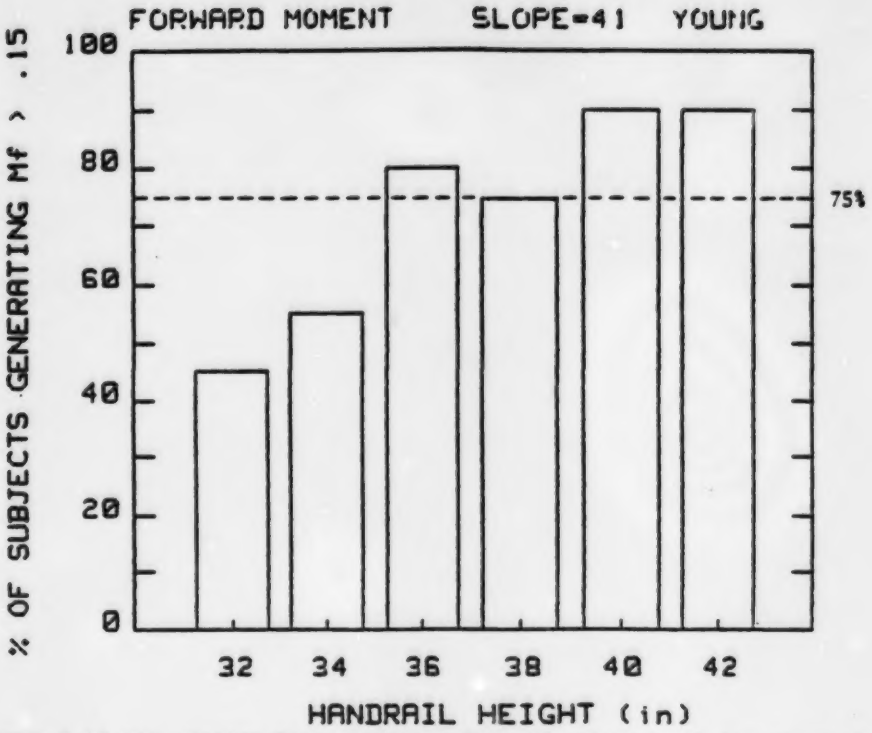


Figure 3.12 (a) Design Range Inferred from Mf, Slope = 41 deg, Young Subjects (Mf = maximum forward moment/body weight moment)

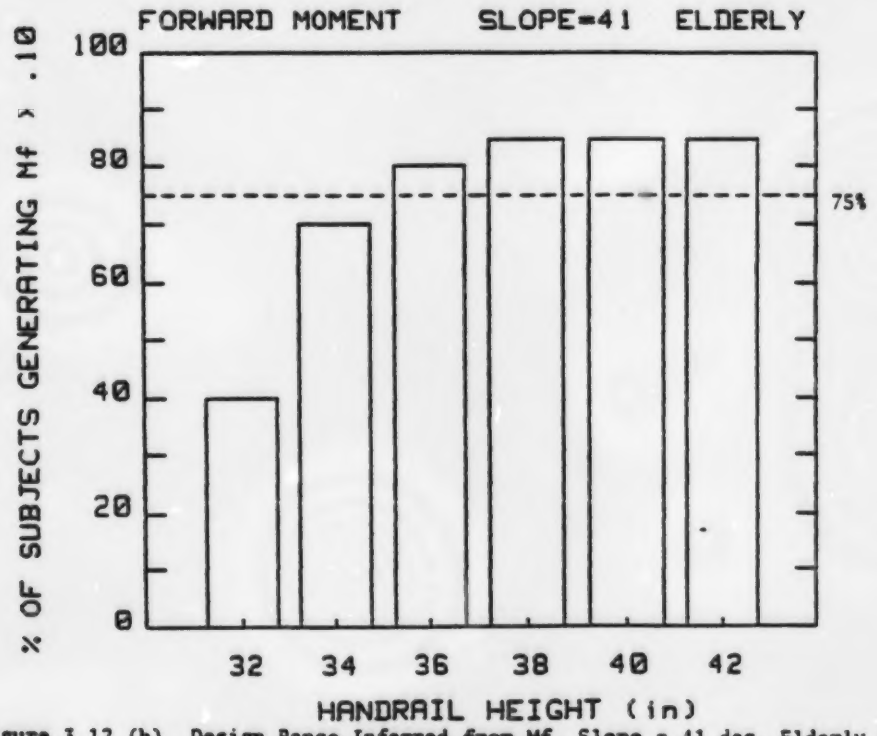


Figure 3.12 (b) Design Range Inferred from Mf, Slope = 41 deg, Elderly Subjects (Mf = maximum forward moment/body weight moment)

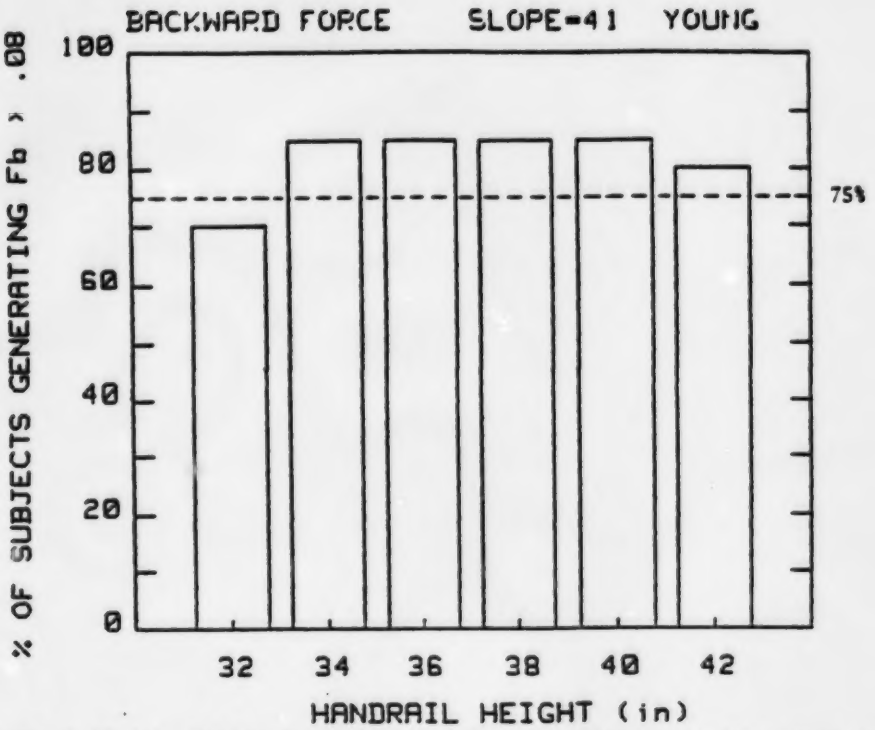


Figure 3.13 (a) Design Range Inferred from Fb, Slope = 41 deg, Young Subjects
(Fb = maximum backward force/body weight)

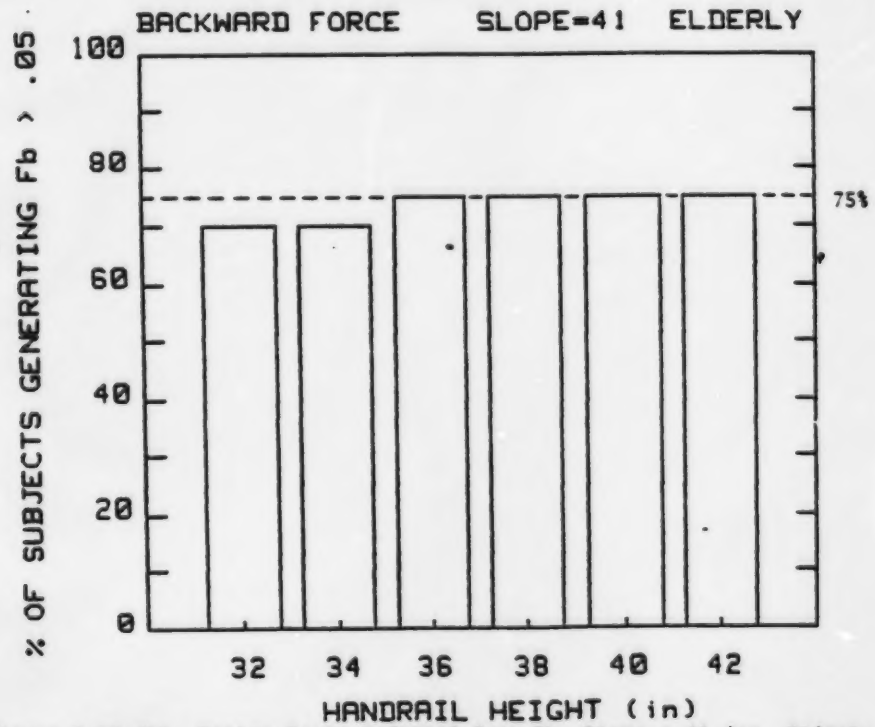


Figure 3.13 (b) Design Range Inferred from Fb, Slope = 41 deg, Elderly Subjects
(Fb = maximum backward force/body weight)

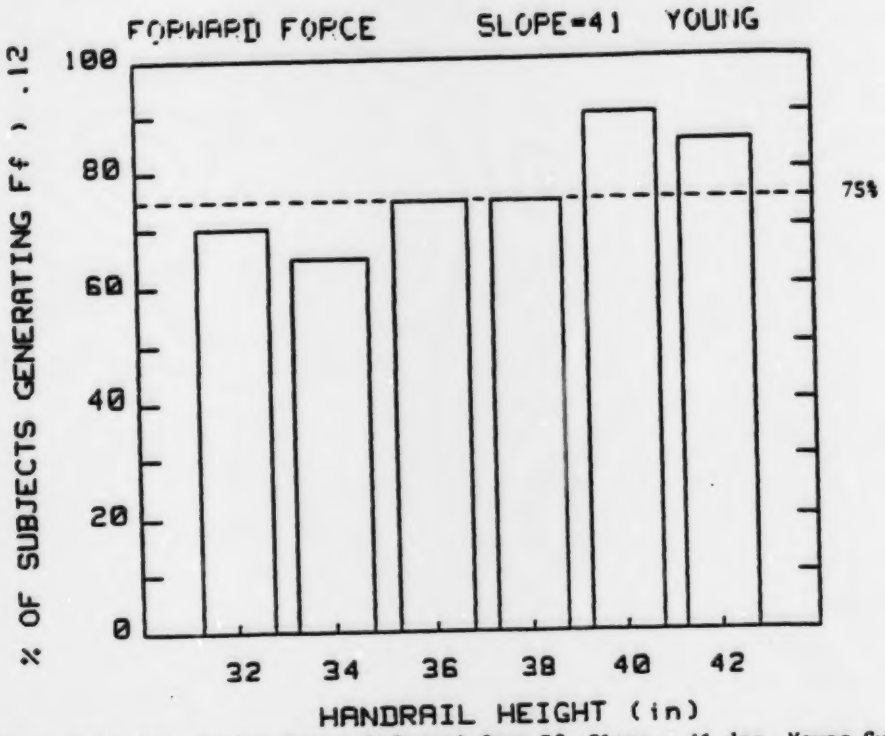


Figure 3.14 (a) Design Range Inferred from Ff, Slope = 41 deg, Young Subjects (Ff = maximum forward force/body weight)

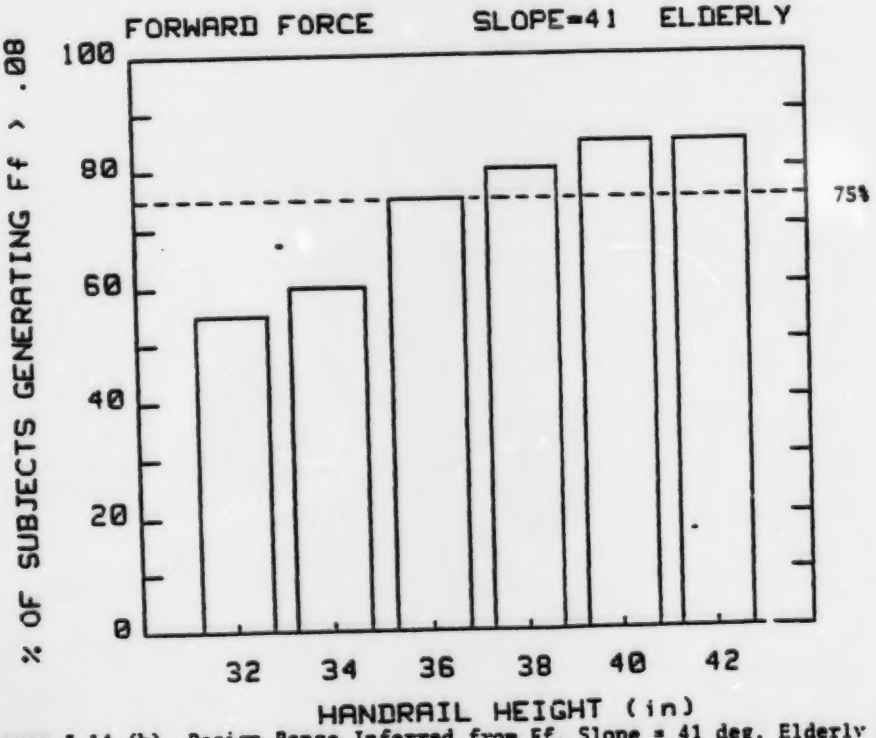


Figure 3.14 (b) Design Range Inferred from Ff, Slope = 41 deg, Elderly Subjects (Ff = maximum forward force/body weight)

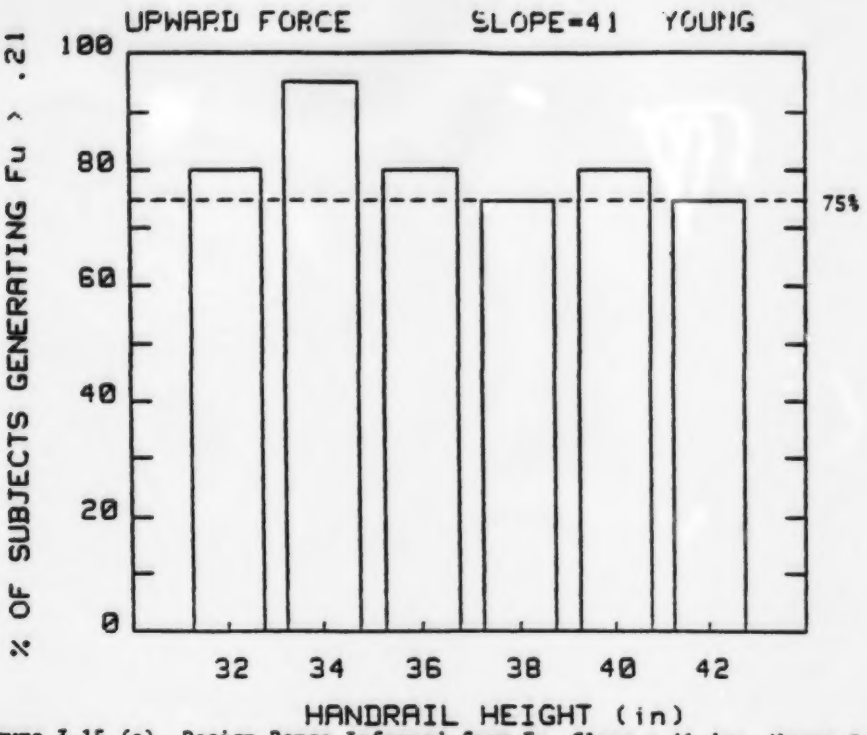


Figure 3.15 (a) Design Range Inferred from Fu, Slope = 41 deg, Young Subjects (Fu = maximum upward force/body weight)

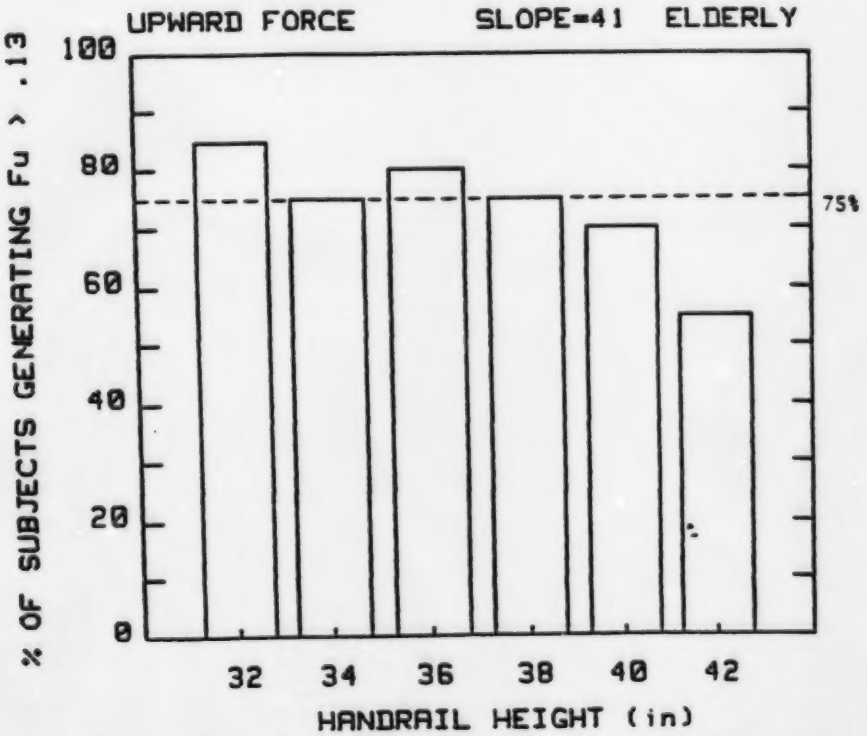


Figure 3.15 (b) Design Range Inferred from Fu, Slope = 41 deg, Elderly Subjects (Fu = maximum upward force/body weight)

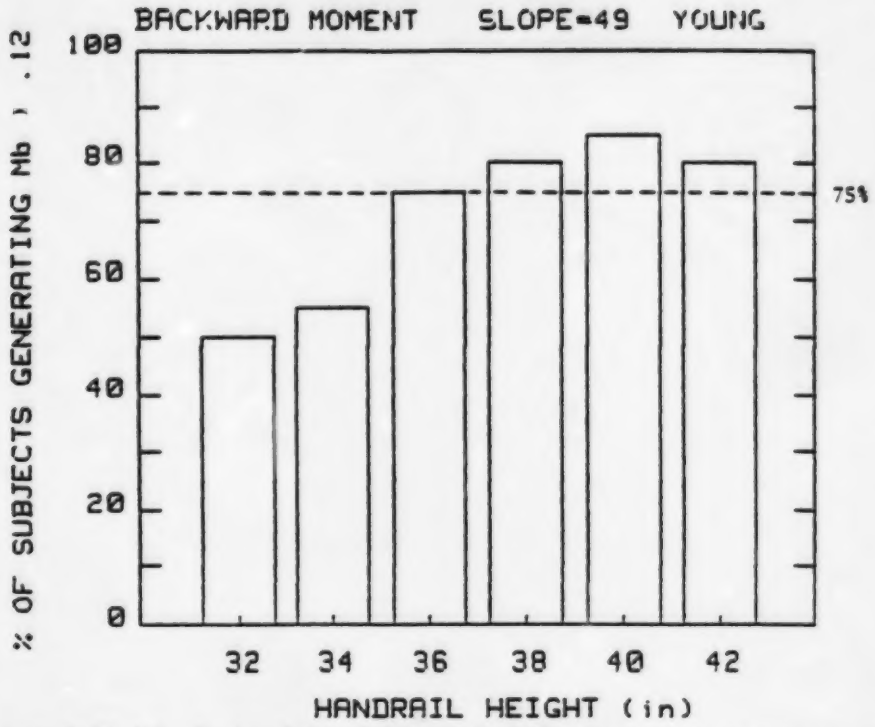


Figure 3.16 (a) Design Range Inferred from Mb, Slope = 49 deg, Young Subjects (Mb = maximum backward moment/body weight moment)

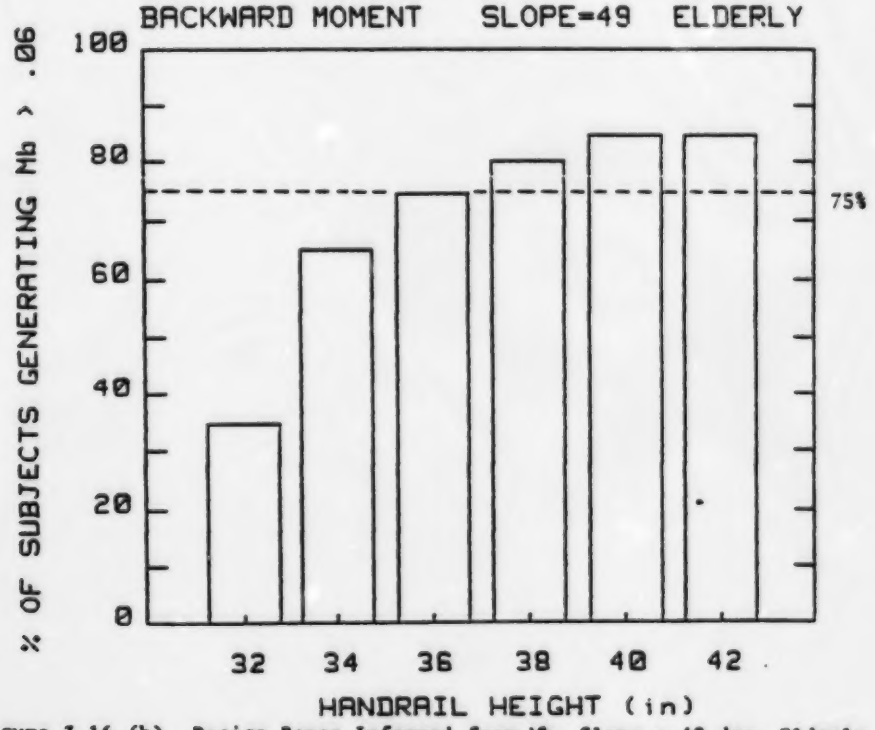


Figure 3.16 (b) Design Range Inferred from Mb, Slope = 49 deg, Elderly Subjects (Mb = maximum backward moment/body weight moment)

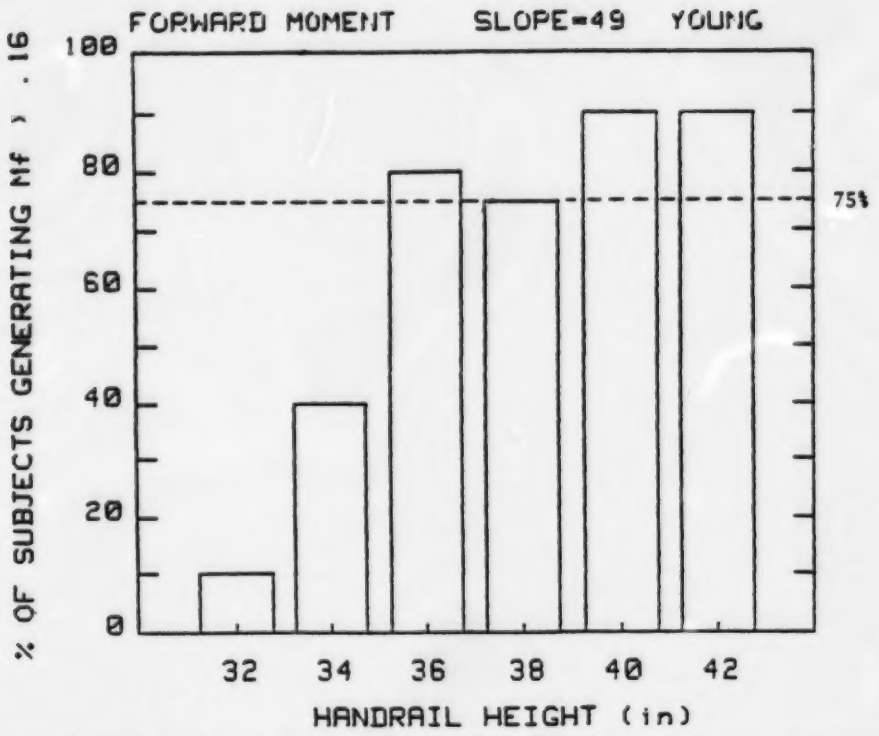


Figure 3.17 (a) Design Range Inferred from Mf, Slope = 49 deg, Young Subjects (Mf = maximum forward moment/body weight moment)

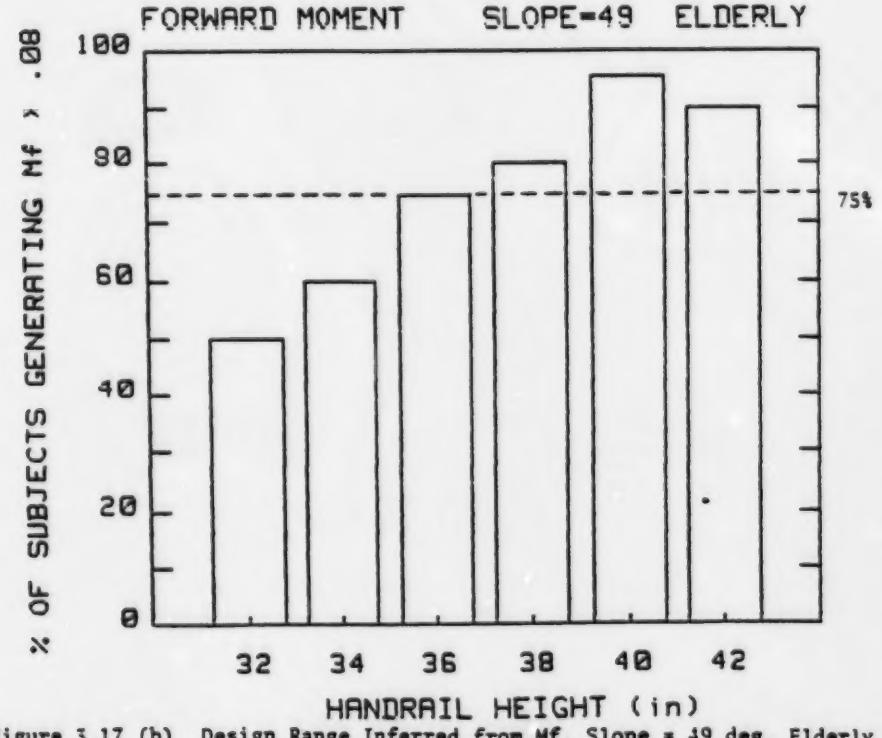


Figure 3.17 (b) Design Range Inferred from Mf, Slope = 49 deg, Elderly Subjects (Mf = maximum forward moment/body weight moment)

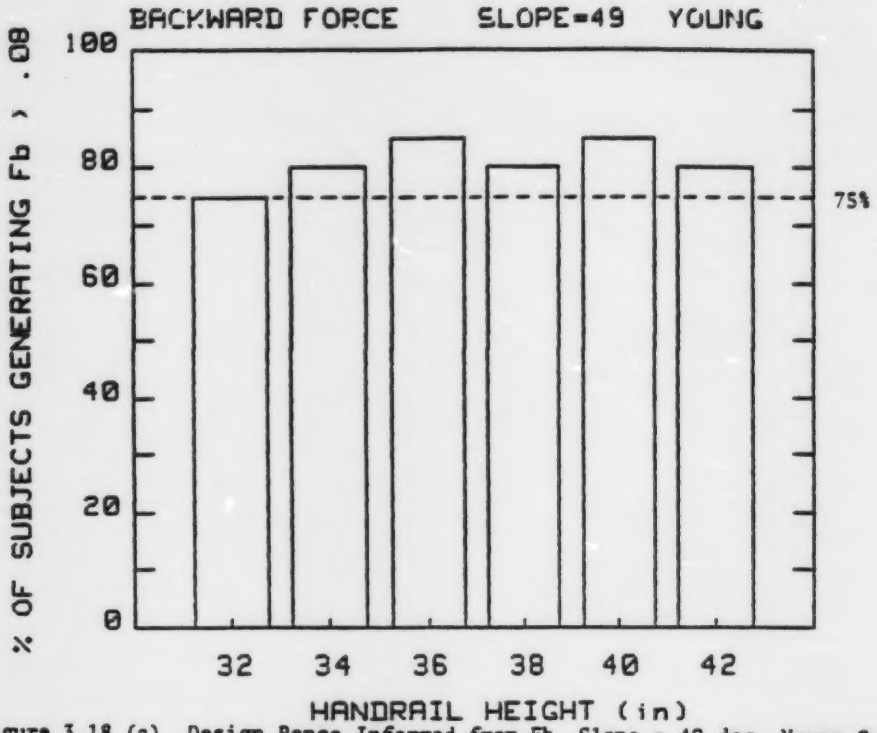


Figure 3.18 (a) Design Range Inferred from Fb, Slope = 49 deg, Young Subjects (Fb = maximum backward force/body weight)

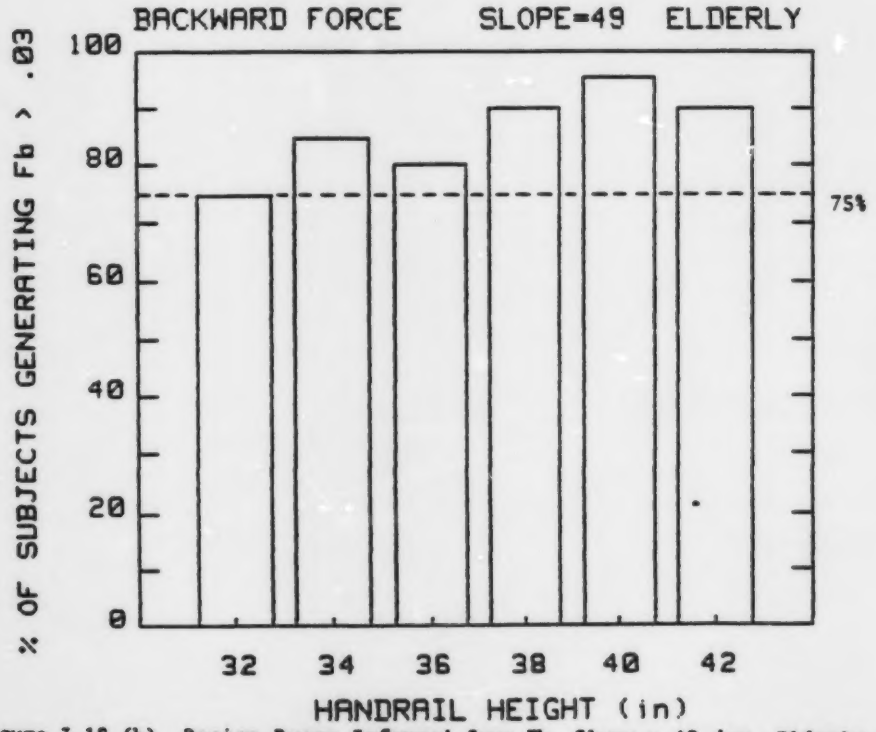


Figure 3.18 (b) Design Range Inferred from Fb, Slope = 49 deg, Elderly Subjects (Fb = maximum backward force/body weight)

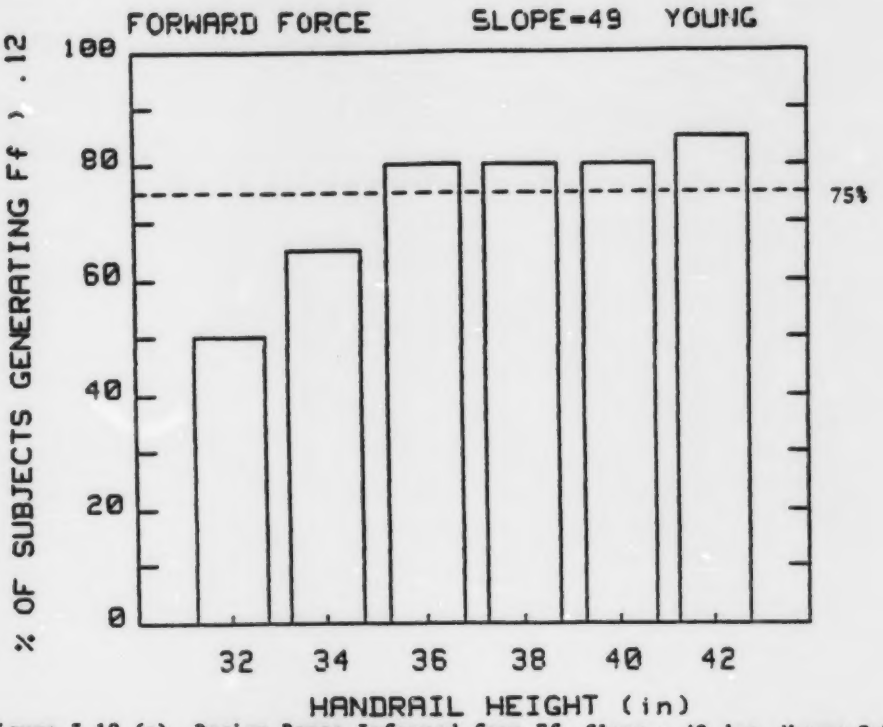


Figure 3.19 (a) Design Range Inferred from Ff, Slope = 49 deg, Young Subjects (Ff = maximum forward force/body weight)

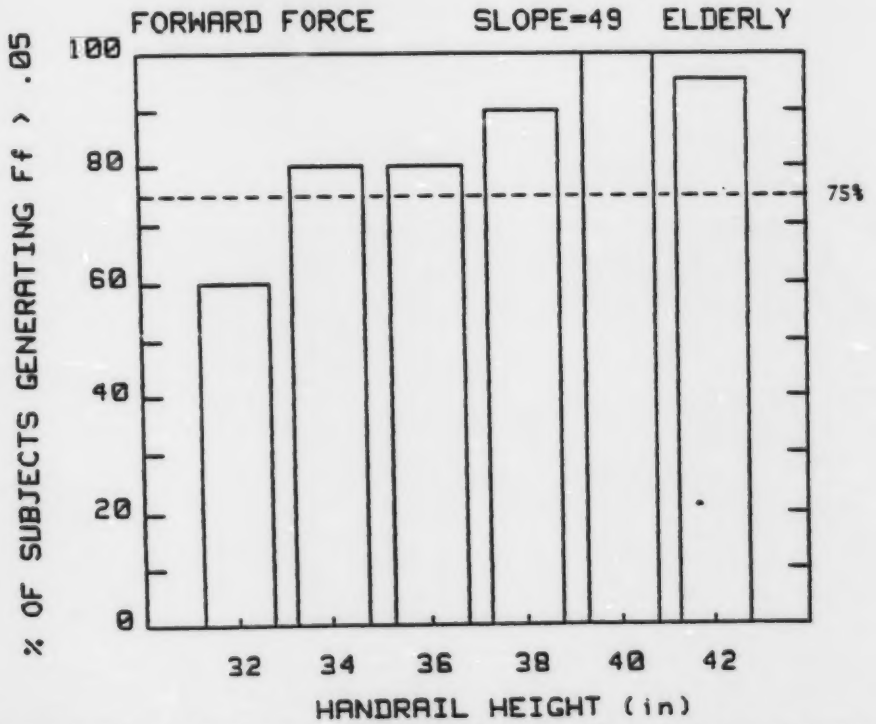


Figure 3.19 (b) Design Range Inferred from Ff, Slope = 49 deg, Elderly Subjects (Ff = maximum forward force/body weight)

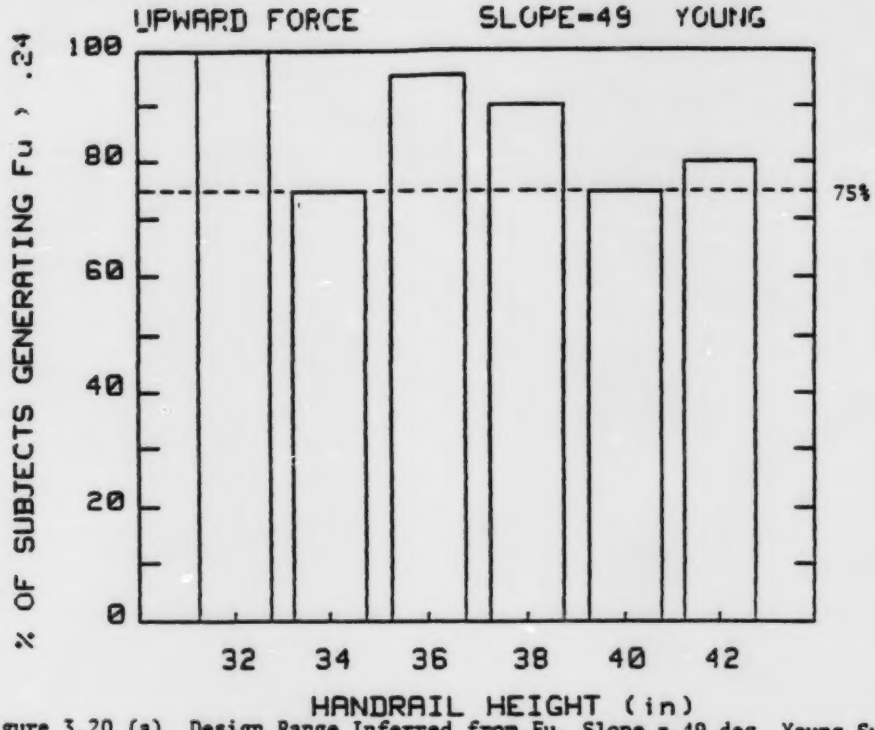


Figure 3.20 (a) Design Range Inferred from Fu, Slope = 49 deg, Young Subjects
(Fu = maximum upward force/ body weight)

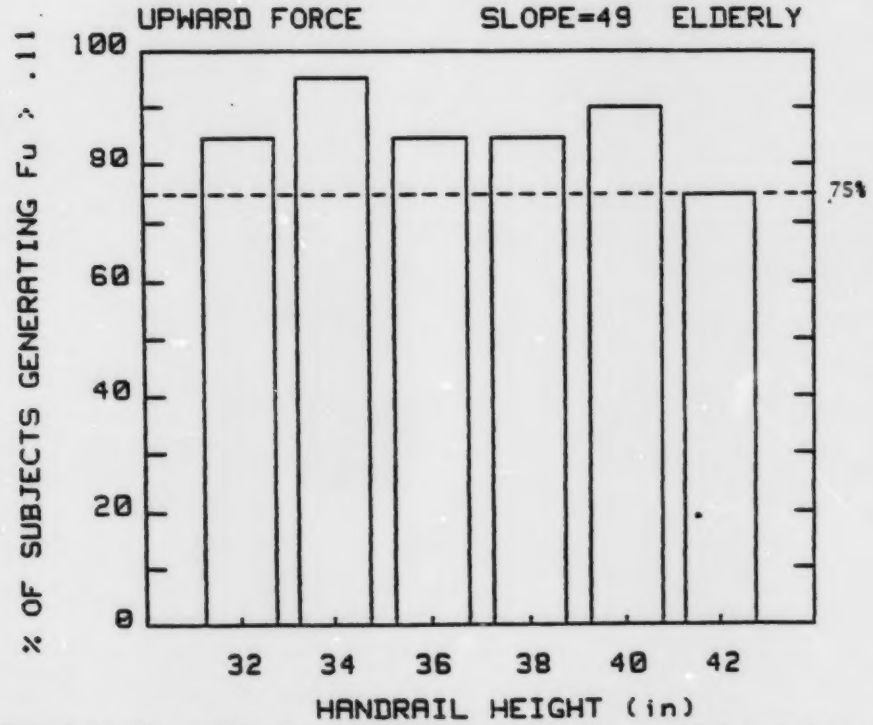


Figure 3.20 (b) Design Range Inferred from Fu, Slope = 49 deg, Elderly Subjects
(Fu = maximum upward force/body weight)

found that these parameters increase with increasing handrail height. Conversely, analysis of parameter Fu points to an upper limit on handrail height for the elderly subjects at the 41-degree slope and for both groups of subjects at the 33-degree slope. Again, this is in agreement with the earlier results, which found that Fu decreases with increasing handrail height.

The overall range is defined as a range of handrail heights that satisfies the requirements derived from the analysis of the individual parameters. For the slopes of 33-degrees and 41-degrees, a design range including all heights between 36" and 38" satisfies the requirements of both age groups. For the slope of 49-degrees, a lower limit of 36 inches satisfies both age groups; however, no upper limit was obtained.

(5) Subjective User Preference

Each subject was asked to select his/her preferred handrail height at each slope, based purely on consideration of comfort. The distributions of the responses are plotted for the young and the elderly subject groups in Figures 3.21 and 3.22.

For both young and elderly subjects and for both stairway slopes, the mean preferred handrail height was approximately 36.5 inches (the mean preferred height was approximately 36 inches at the 33-degree slope).

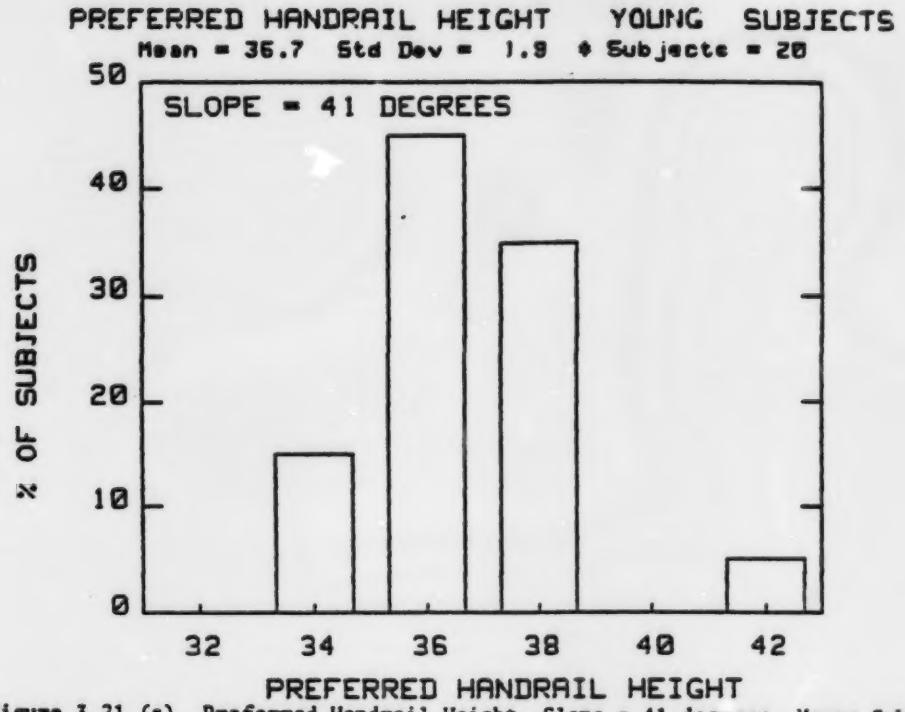


Figure 3.21 (a) Preferred Handrail Height, Slope = 41 degrees, Young Subjects

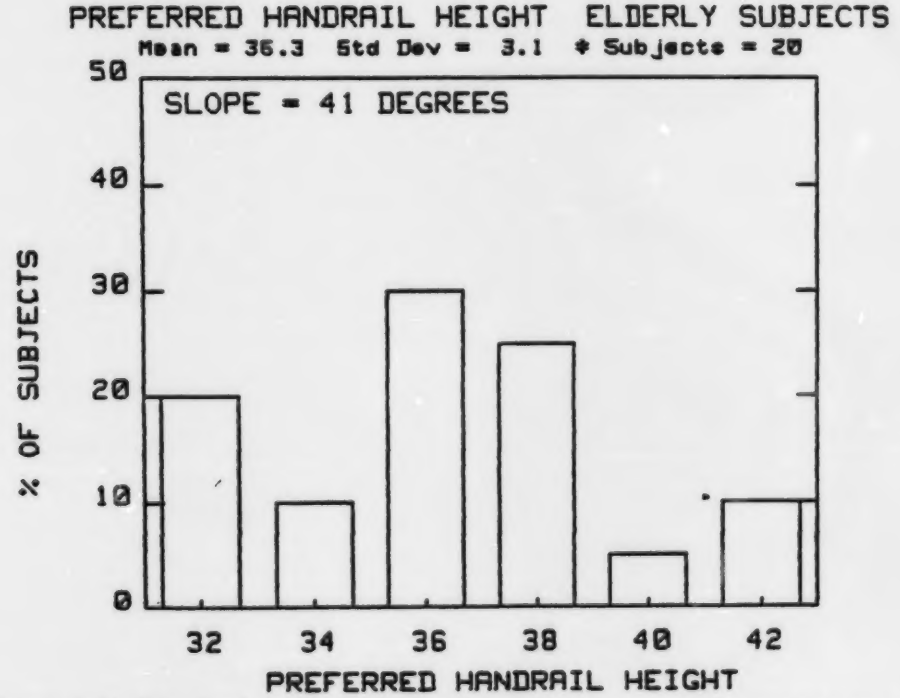


Figure 3.21 (b) Preferred Handrail Height, SLope = 41 degrees, Elderly Subjects

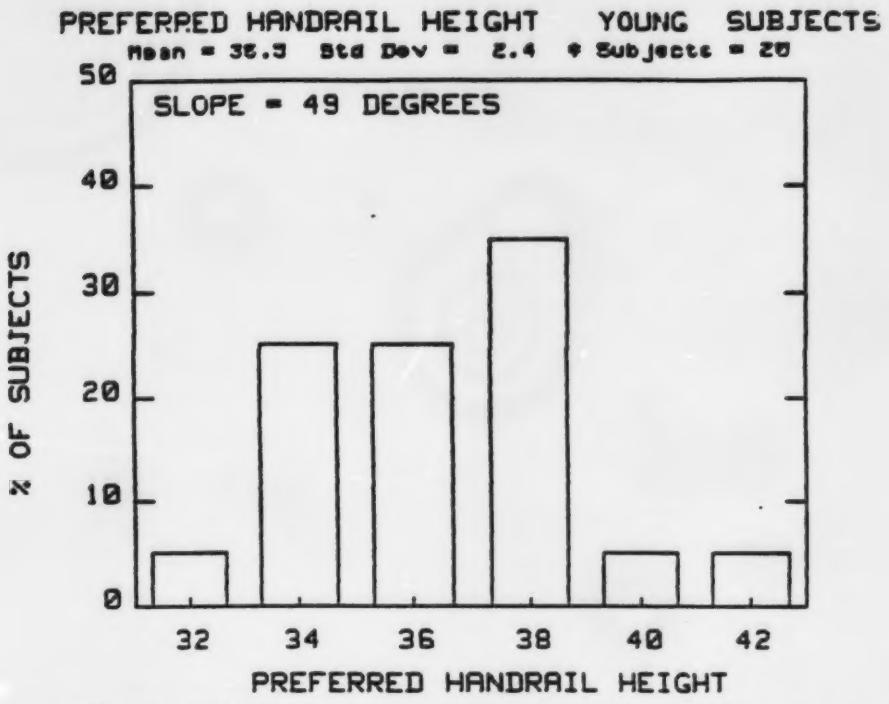


Figure 3.22 (a) Preferred Handrail Height, Slope = 49 degrees, Young Subjects

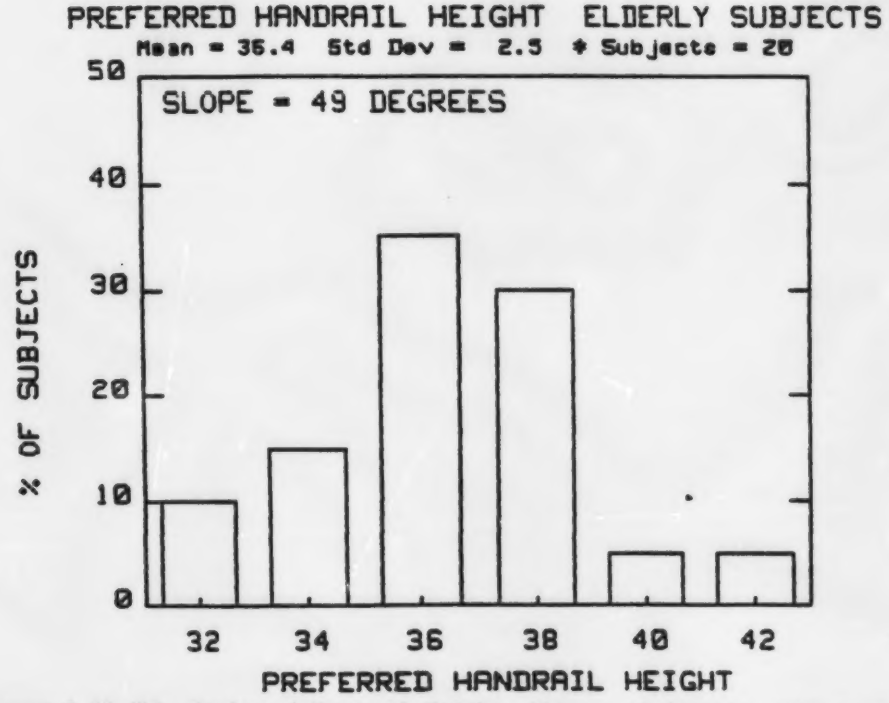


Figure 3.22 (b) Preferred Handrail Height, Slope = 49 degrees, Elderly Subjects

IV DISCUSSION OF RESULTS

(1) Biomechanics

Due to the redundant degrees of freedom of the arm, grip location is not constrained; therefore, choice of grip location is based on another consideration, such as comfort. Presumably, comfort is maximized over some range of wrist, elbow and shoulder angles. Measurements of grip location (see Appendix C) indicated that individuals tend to cope with increases in handrail height by moving their grip forward rather than increasing flexion at the elbow. This was found to be true at both stairway slopes tested in the present study, as well as at the slope tested in the previous study.

A change in stairway slope has two effects: (1) the actual height of the handrail is changed at all points except the point at which handrail height is measured (i.e. in the plane of the riser), and (2) the angular orientation of the handrail is changed. Both factors will affect the wrist, elbow and shoulder angles used in achieving a grip on the handrail. The resulting changes in muscles lengths and skeletal lever arms will affect force generation. In addition, the user's choice of grip location will likely change, if we can assume that the user will choose those joint angles that maximize comfort. Changes in grip location will change the moment arm of the handrail force about the MP joint axis and thereby influence moment generation.

The higher handrail heights (i.e. 40 and 42 inches) presented difficulty for some subjects, in that they were unable to grasp the handrail without resting part of the arm along the handrail. This was not a problem at the slope of 33 degrees. The effect of a higher slope is to increase the height of the handrail at all points posterior to the riser. Thus, the portion of the handrail adjacent to the body is higher and more likely to interfere with arm placement.

A stepwise regression was performed to determine which anthropometric factors had the greatest influence on the ability to generate stabilizing forces and moments. In this analysis, regressions are performed sequentially, each time including the new variable that generates that largest increase in the correlation coefficient. The independent variables included the independent variables in the linear model described earlier plus subject characteristics such as sex, weight, height, hand length and arm dimensions.

The results of the stepwise regression showed hand length to be the dominant anthropometric factor in almost all cases. Other characteristics such as weight, height and upper and lower arm length had a significant influence but only for certain force and moment parameters.

(2) Comparison with Previous Study

The results obtained at slopes of 41 and 49 degrees are very similar to the previous results obtained at a slope of 33 degrees. At all three slopes: (1) significant differences existed between the mean forces and moments generated at the different handrail heights, (2) there was a strong linear dependence of forces and moments on handrail height (forward/backward moment and forward/backward force increased while upward force decreased with increasing handrail height), and (3) the recommended design range was the same (i.e. 36 to 38 inches). However, the present study has not replicated completely the findings of the previous work. For example, the present data failed to show a common slope for several of the force and moment parameters, and the histogram analysis found an upper limit for handrail height in only one case (elderly subjects at 41-degrees).

Some of the present data seems to show somewhat greater random variation than the data from the previous study. This variation is evident in the "raw" data (Figures 3.1 to 3.10) and could account for the failure to replicate all the findings of the previous study. The greater variability could be due to difficulty in exerting forces on steep handrails. If the handrail grip feels awkward, then one might expect less consistency in a subject's ability to generate maximum force at every handrail height.

For some of the subjects in the present study, the generated forces and moments tend to drop off at both the lower and higher handrail heights, exhibiting more of a quadratic than a linear dependence on handrail height. However, this trend was not statistically significant.

(3) Age Differences

The significant age differences seen could be due to a number of factors. Lower levels of force and moment can be explained in terms of the decrease in muscle strength which occurs in aging, or to the differences in the relative numbers of males and females in the two subject groups tested. (The male-to-female ratio was 0.82 in the young group, and 0.67 in the elderly group.)

Age-related reduction in stature might be expected to result in the elderly subjects placing their hands farther forward; reduction in range of elbow flexion might also have the same effect. Such a trend is suggested by the grip location data in Appendix C. The differences in grip location may explain the differences between the two age groups in the dependence of their force/moment generating capability on handrail height.

(4) Estimation of the Optimal Design Range

The method by which the optimal design range was calculated does not lend itself to a statistical analysis of significance. Furthermore, in calculating the design range, the definition of

"acceptability" (based on 75% of the subjects) was chosen on an operational basis, to allow a reasonably narrow range to be specified. Therefore, the results should be treated only as a rough estimate of the optimal design range for handrail height.

Consideration of subjective user preference is important. If the stairway users feel that a particular handrail is uncomfortable or awkward to use, then they may decide not to use the handrail. In this situation, it is much more difficult to recover from a loss of balance without falling, due to the time delay associated with the grabbing response. Thus, the biomechanical advantages of a particular handrail could be negated.

The analysis of the experimental results suggested a lower limit of 36" for all three slopes. However, no upper limit was found for the young subjects at the 41-degree slope or for either age group at the 49-degree slope. The increase in ability to generate forward/backward forces and moments with increasing height might suggest using the highest height possible; however, consideration of user comfort will place an upper limit on handrail height as discussed above. At all three slopes, a large majority of the subjects (approximately 90%) had preferred heights below 40"; therefore, 38" might represent a reasonable upper limit on acceptable handrail height.

(5) Limitations of the Present Study

The erect posture is a reasonable approximation of body position at the beginning of a fall. Thus, the static force measurements made in this position should give an indication of the maximum stabilizing forces and moments that could be generated at the start of a fall. Measurement of maximal values provides a suitable basis for comparing different handrail designs; however, there is no implication that these levels of force and moment would actually be generated during a fall. Other factors (e.g. time delay in the individual's response) may prevent the subject from attaining his/her maximal capabilities. Furthermore, as the body proceeds to fall forward, the actual forces and moments that can be exerted will change due to positional changes of the body relative to the handrail. In addition, muscle force generation will change under dynamic conditions.

Although the stabilizing force and moment exerted during an actual fall may vary considerably due to the dynamic and positional effects discussed above, increased capability for generating stabilizing forces and moments during the initial stages of a fall would be expected to correlate with an increased probability of balance recovery. Therefore, static measurements made in an erect position should provide a useful basis for selection of handrail height in building design.

Experimental verification of this hypothesis would be valuable, but is beyond the scope of the present work. Such experiments could involve applying postural perturbations to subjects and observing their

ability to prevent loss of balance, using handrails of different height. Because of safety concerns, any studies involving actual loss of balance would have to preclude elderly subjects; however, there is no reason why healthy, young volunteers could not be studied, provided that appropriate safety measures are taken (e.g. padding surfaces, wearing of safety harnesses, etc).

The results of the present study represent a significant advance over previously existing knowledge of stairway safety and are therefore recommended for use as a basis for selection of handrail height in building design, at least until such time as dynamic perturbation studies can be carried out to verify the relevance of the static measurements.

V CONCLUSIONS

(1) Handrail height has a significant influence on the ability to generate stabilizing forces and moments.

(2) The ability to generate stabilizing forces and moments at a given stairway slope varies linearly with handrail height.

(i) For backward and forward moment and for backward and forward force, the normalized magnitude of the force or moment increases with increasing handrail height.

(ii) For upward force, the normalized magnitude decreases with increasing handrail height.

(iii) For the majority of the normalized forces and moments, all individuals in a given age group have the same linear dependence on handrail height (i.e a common slope at each parameter). The magnitude of the linear slope is dependent on stairway slope.

(iv) The "relative magnitudes" (i.e. y-intercepts) of the forces and moments generated by each individual are significantly different from those generated by other individuals.

(3) There are significant age-related differences in the ability to generate stabilizing forces and moments.

(i) On the average, young individuals exert larger forces and moments, relative to body weight and size, than elderly individuals.

(ii) Although qualitatively the same, the quantitative dependence of force/moment generating capability on handrail height is often different for the two age groups.

(4) The optimal design range for handrail heights is estimated to be substantially the same for both young and elderly subjects at both stairway slopes (41 and 49 degrees). This design range is the same as that estimated previously for a stairway slope of 33 degrees.

(i) The lower limit on handrail height is estimated to be 36 inches (0.914 meters).

(ii) The upper limit on handrail height is estimated to be 38 inches (0.965 meters).

(5) In terms of comfort, the mean preferred handrail height of both the young and elderly subjects is approximately 36.5 inches (0.914 meters) for stairway slopes of 41 and 49 degrees.

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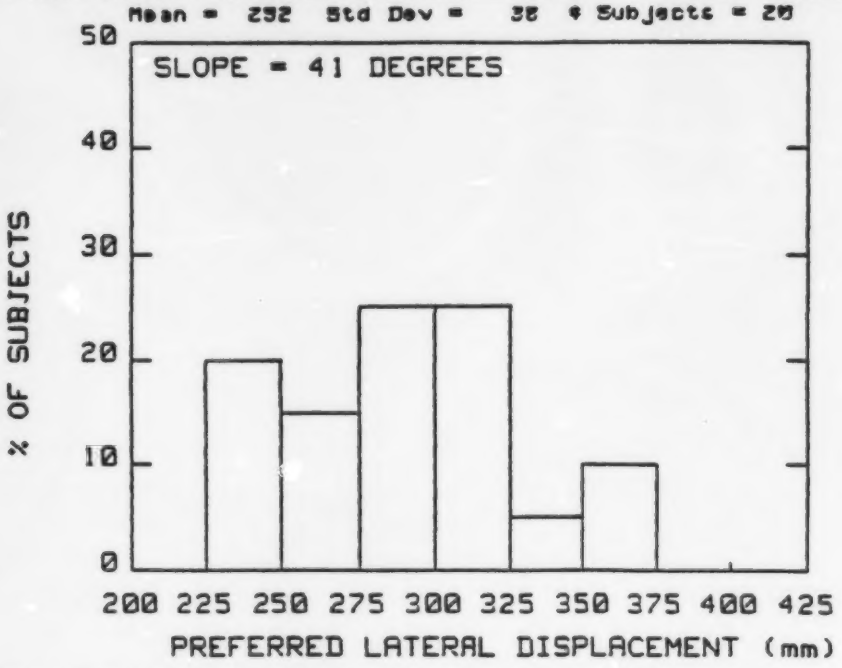
APPENDIX A

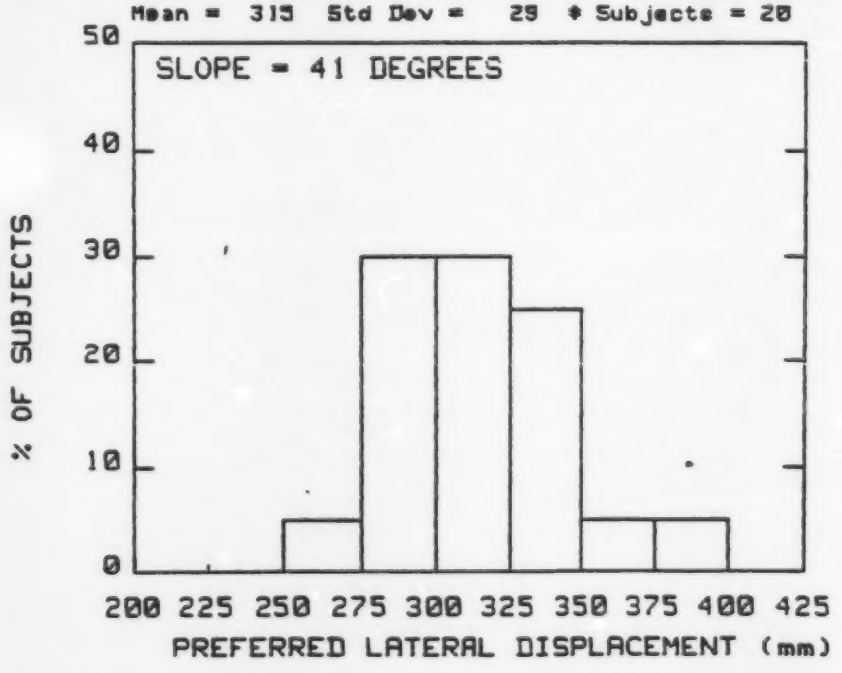
PREFERRED LATERAL DISPLACEMENT

PREFERRED LATERAL DISPLACEMENT* YOUNG SUBJECTS

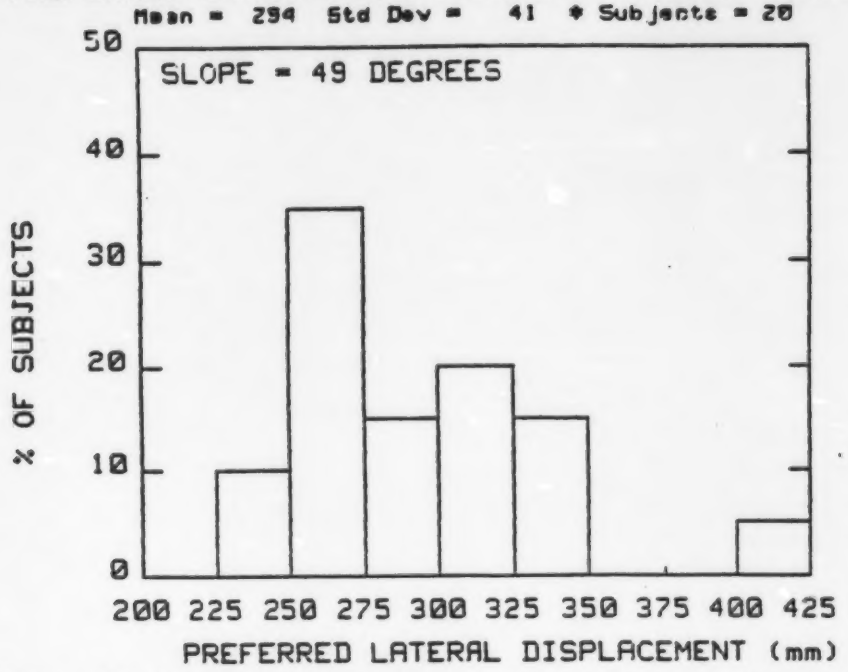


*Note: The displacement is the distance between the centre-line of the body and the centre-line of the handrail.

PREFERRED LATERAL DISPLACEMENT* ELDERLY SUBJECTS

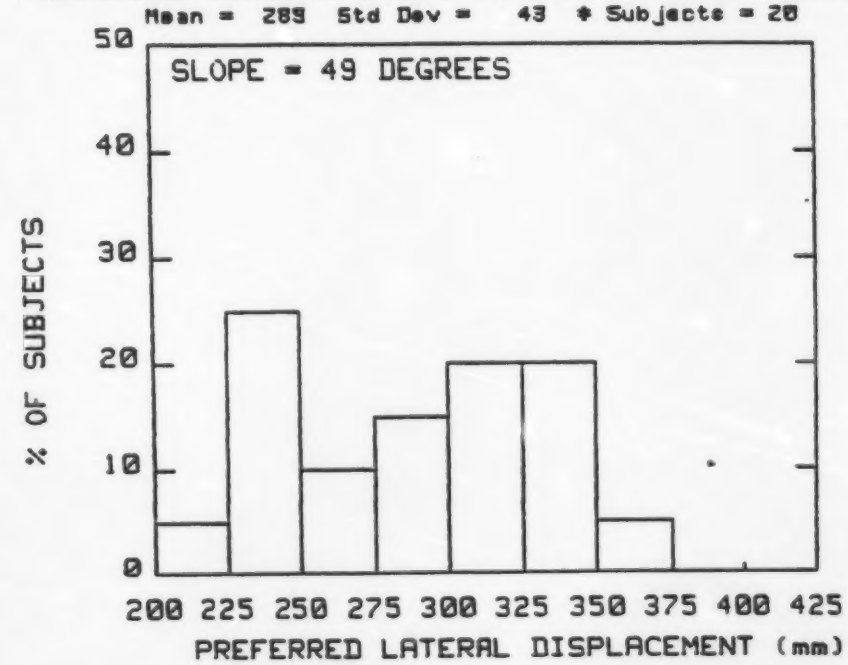


PREFERRED LATERAL DISPLACEMENT* YOUNG SUBJECTS



*Note: The displacement is the distance between the centre-line of the body and the centre-line of the handrail.

PREFERRED LATERAL DISPLACEMENT* ELDERLY SUBJECTS

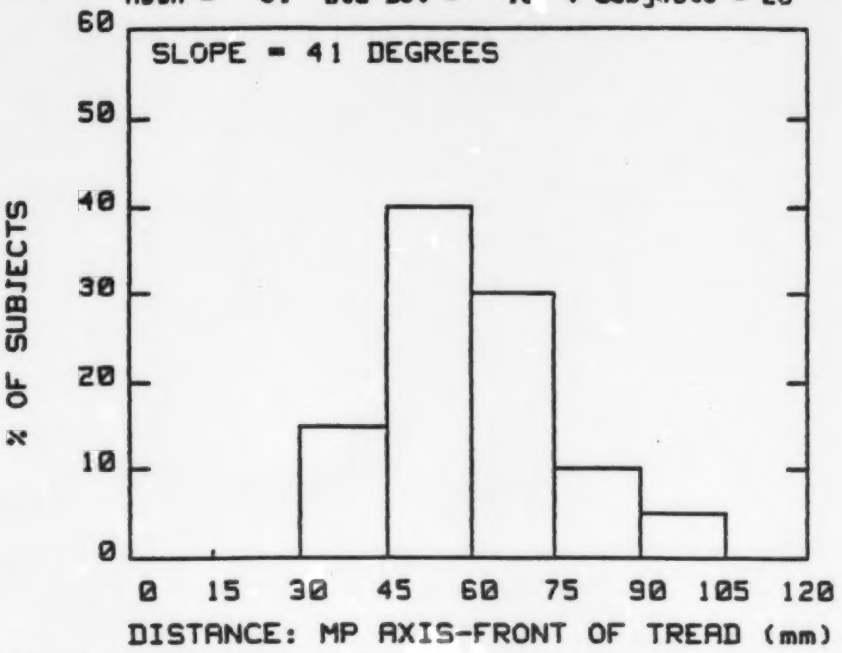


APPENDIX B

LOCATION OF METATARSOPHALANGEAL JOINT RELATIVE TO THE STAIRWAY TREAD

LOCATION: METATARSOPHALANGEAL AXIS* YOUNG SUBJECTS

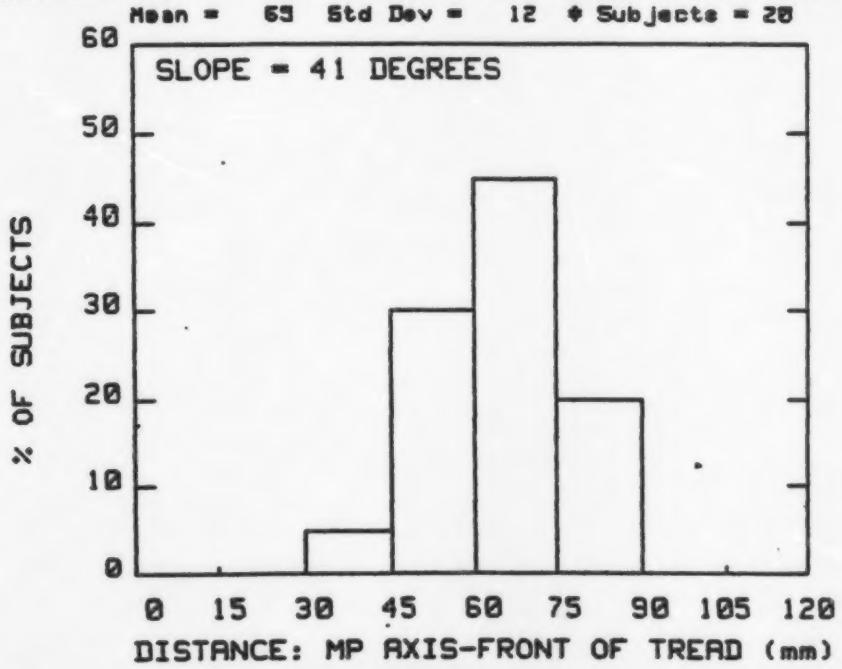
Mean = 61 Std Dev = 18 # Subjects = 20



*Note: The distance from the MP axis to the front of the tread is negative if the MP axis overhangs the front of the tread.

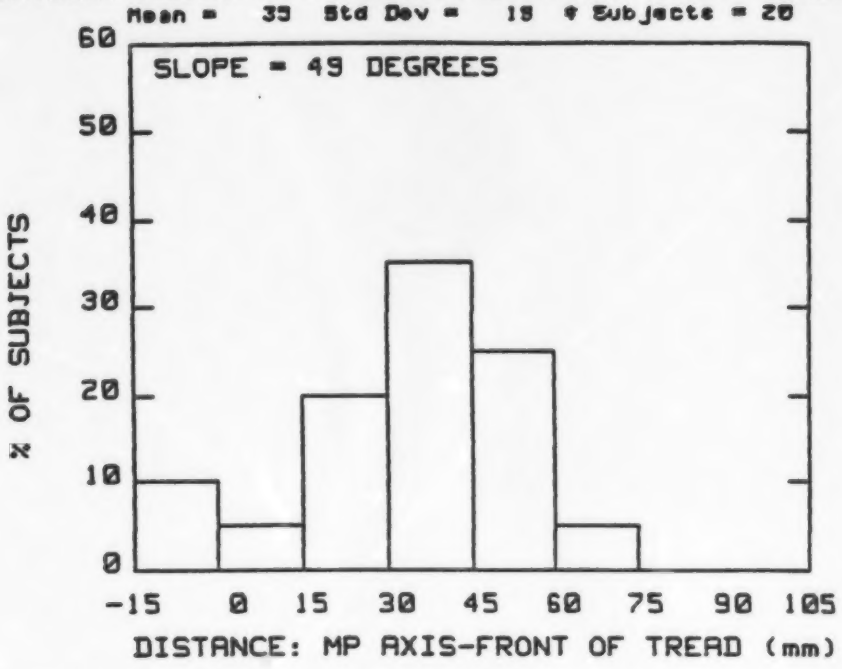
LOCATION: METATARSOPHALANGEAL AXIS*; ELDERLY SUBJECTS

Mean = 63 Std Dev = 12 # Subjects = 20



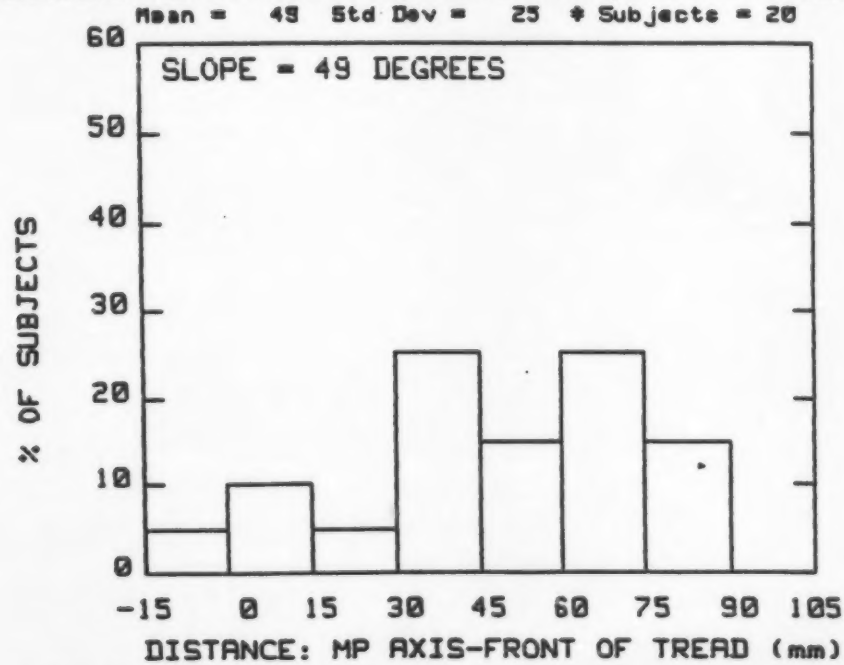
NOTE: Use caution in extrapolating from these results to actual stairway use. The posterior riser was replaced with the backboard; hence, there was no projected nosing behind the subjects' legs.

LOCATION: METATARSOPHALANGEAL AXIS*; YOUNG SUBJECTS



*Note: The distance from the MP axis to the front of the tread is negative if the MP axis overhangs the front of the tread.

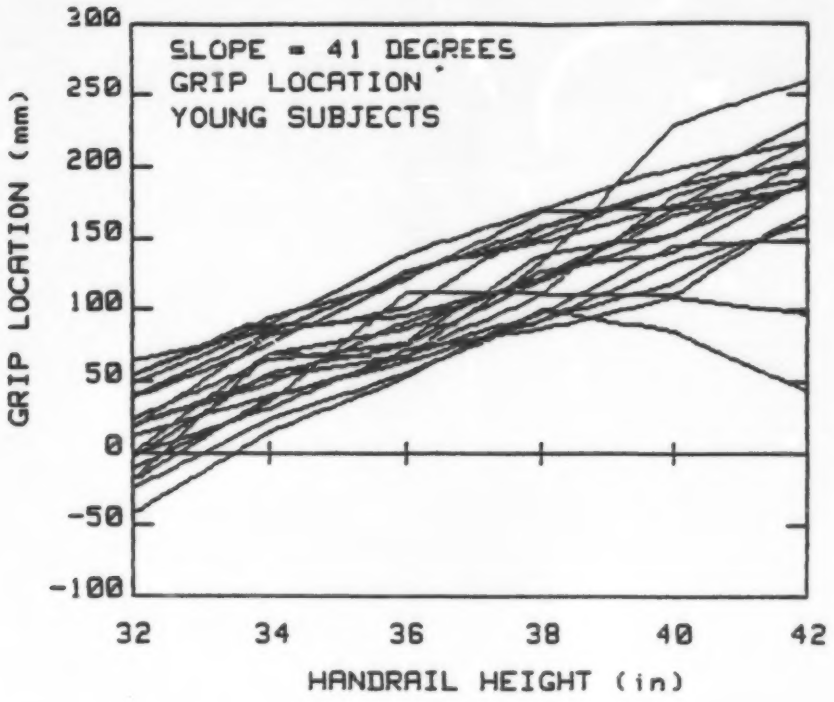
LOCATION: METATARSOPHALANGEAL AXIS*; ELDERLY SUBJECTS



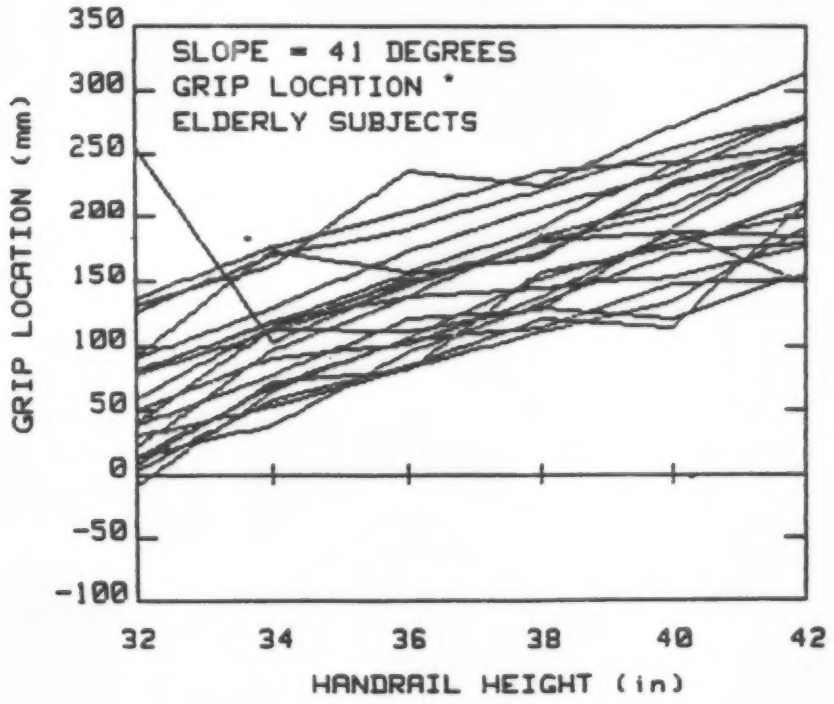
NOTE: Use caution in extrapolating from these results to actual stairway use. The posterior riser was replaced with the backboard; hence, there was no projected nosing behind the subjects' legs.

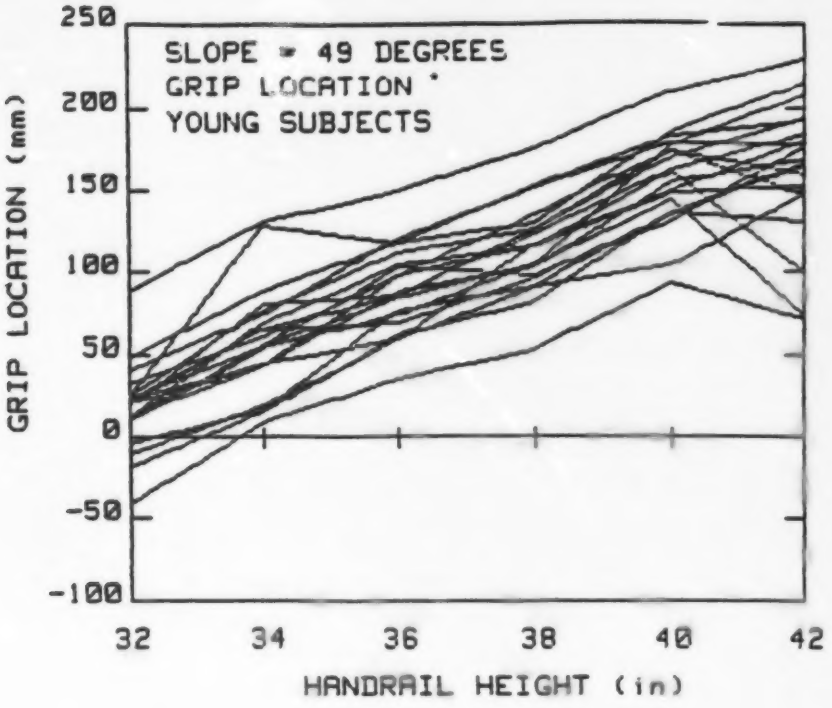
APPENDIX C

GRIP LOCATION



*Note: The grip location is the horizontal distance from the plane of the anterior riser to the most anterior point of the hand.





* Note: The grip location is the horizontal distance from the plane of the anterior riser to the most anterior point of the hand.